HYDROSEEDING FOR RESTORING DEGRADED SEMI-ARID MEDITERRANEAN ENVIRONMENTS: A REVIEW OF CHALLENGES

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ABSTRACT

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Hydroseeding is a restoration technique commonly used in varied restoration projects. This literature review, encompassing about 100 published research papers from 1990 to 2020, revealed numerous limitations in a semi-arid Mediterranean environment. Challenges facing hydroseeding as a restoration tool in semi-arid Mediterranean environments were evaluated by analyzing different factors affecting ecological and technical levels. This issue was approached by sorting variables under either biotic or abiotic factors, further sub-dividing them under either natural-environmental or human-influenced factors. The review highlighted several constraints when applying hydroseeding techniques in a semi-arid Mediterranean environment: Slope steepness, slope aspect, high water runoff, low presence of water, mixing solutions used, and high cost for applying this technique are some of those constraints facing its success. Other shortcomings are related to the low success rate of commercial seed mixtures under harsh conditions, and their tendency to compete with native species. Moreover, the review provided recommendations to increase hydroseeding success by using varied techniques such as topsoil spreading, using native seeds, Mycorrhizal, or Rhizobium inoculation, and the use of nurse plants. Furthermore, environmental psychology approach was suggested as means to convey a better message and increase acceptability towards improved innovative suggestions.

Keywords: abiotic, biotic Factors, Limitations, success, failures, restoration techniques

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INTRODUCTION

Vegetation is a cornerstone of natural ecosystems. It is not only an essential habitat for different living species but also carries ecosystem services and functions such as nutrient cycling, soil protection, water purification, etc. (Hölzel et al., 2012). Numerous factors lead to ecosystem degradation and surface modifications with irreversible loss of soils via removal of upper soil, sedimentation, or salinization, etc. Whenever a certain threshold level is crossed, it cannot reverse back without interventional correction to alternate what led to that threshold being crossed (Aronson et al., 1993). This fact is especially valid for semi-arid Mediterranean ecosystems, where natural recovery after the disturbance has been recognized to be harder than other ecosystem types (Blondel et al., 2010). In such conditions, ecological restoration techniques are required to initiate, assist, and accelerate recovery of degraded ecosystems with respect to their structure, functional properties, and exchanges with surrounding landscapes (Society for Ecological Restoration [SER], 2004). Restoration is not easy and straightforward because of several factors restricting its success, such as abiotic and biotic constraints (Bakker and Berendse, 1999).

One important restoration technique applied to reintroduce vegetation is manual seeding, where seeds are hand spread with no specialized equipment. Such a manual method is suitable only for small areas (MacDonald et al., 2015). Drill seeding is another practice that involves seed application, utilizing conventional agricultural equipment below the soil surface. This practice is limited to relatively flat and well-groomed sites (MacDonald et al., 2015). Hydrotechnology is another commonly used technique (Figure 1), especially on steep slopes and inaccessible regions (Davy, 2002). The process consists of mixing cellulose fiber, mulch, seeds, and later adding water into the tank and spraying the degraded area (Martin et al., 2002). Although used worldwide (more than 12 million km length of road networks in the United States, Europe, Japan, and Australia - http://www.piarc.org), hydroseeding has variable outcomes.
Figure 1. Utilizing hydroseeding technique as a restoration tool on a steep road cut slope.

The Mediterranean region (Figure 2) covers about 850 million hectares in 22 countries across Southern Europe, the Middle-East, and North Africa (Zdruli, 2014). In this vast region, hydroseeding as a restoration tool is increasingly applied (Andre’s et al., 1996; Albaladejo et al., 2000; Matesanz et al., 2006; Tormo et al., 2007). A study from around the Mediterranean Basin, spanning over sixteen countries, surveyed 36 implemented restoration projects revealed that 17% of the total executed restoration projects were undertaken through hydroseeding practices and were carried out on post-industrial sites (mining), infrastructure development, deforestation, and drought sites (Nunes et al., 2016). In several cases, poor results in plant performance have been measured (Matesanz et al. 2006). Several direct and indirect variables determine the effectiveness of hydroseeding in semi-arid Mediterranean environments. This assessment should cover varied factors such as soil conditions, topography, season, climate, vegetation types, water availability, vulnerable or sensitive surrounding areas, and maintenance requirements. Once identified, those factors could be manipulated to improve restoration efforts (Tormo et al., 2008).
Successful restoration results from a combination of ecologically sound projects that are technically possible, financially feasible, and are socially acceptable (Khater, 2015). Höltzel et al. (2012) distinguished various factors affecting ecological restoration under three major headings: starting conditions, abiotic factors, and biotic factors. This paper presents a review of more than 100 research papers published between 1990 and 2020, reporting the success and failure of hydroseeding as a restoration technique for large-scale projects. It analyzes the reported cases in view of biotic and abiotic factors potentially affecting restoration success and differentiates between nature-based and human-related variables.

**METHODS**

The different variables affecting hydroseeding successes and failures in a semi-arid Mediterranean environment were assessed through exploiting diverse search engines (Google Scholars, Web of science, summon 2.0), searching in the title, abstract, and keywords of papers the following terms: “hydroseeding” plus “semi-arid Mediterranean environment” plus “cultural practices”, “microclimate”, “nurse plants”, “seed type/competition/inoculation”, “slope aspect/steepness”, “soil addition/mulching”, or “mixing solutions” (See Table 1).

Table 1. Primary and secondary keywords used to filter and select the papers used in the methodology.

| Primary Search Key Words | Secondary Search Key Words | Author(s) | Title | Year of Publication |
|--------------------------|----------------------------|------------|-------|---------------------|
| Hydroteeding Semi-arid   | History/procedures         | Albaladejo Montoro, J. Alvarez Rogel, J. Querejeta, J | Three hydro-seeding revegetation techniques | 2000 |

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| Mediterranean environment | for soil erosion control on anthropic steep slopes. | Andres, P. Zapater, V. Pamplona, M. | Stabilization of motorway slopes with herbaceous cover, Catalonia, Spain. Restoration Ecology 4:51-60 | 1996 |
|---------------------------|---------------------------------------------------|---------------------------------------|--------------------------------------------------------------------------------------------------|------|
| Hölzel, N. Buisson, E. Dutoit, T. | Species introduction—a major topic in vegetation restoration. | 2012 |
| Khater, C. | L’écologie appliquée : une responsabilité scientifique au carrefour de l’interdisciplinarité. | 2015 |
| Matesanz, S. Valladares F. Tena D. Costa-Tenorio M. Bote D. | Early dynamics of plant communities on revegetated motorway slopes from Southern Spain: is hydroseeding always needed? | 2006 |
| Mola, I. Jiménez MD. López-Jiménez, N. Casado, MA. Balaguer, L. | Roadside reclamation outside the revegetation season: management options under schedule pressure. | 2011 |
| Nunes, A. Oliveira, G. Mexia, T. Valdecantos, A. Zucca, C. Costantini, EA. Abraham, EM. Kyriazopoulos, AP. Salah, A. Prasse, R. Correia, O. | Ecological restoration across the Mediterranean Basin as viewed by practitioners. | 2016 |
| Tormo, J. García-Fayos, P. Bochet, E. | Relative importance of plant traits and ecological filters in road embankment revegetation under semiarid Mediterranean conditions. | 2008 |
| Zdruli, P. | Land resources of the Mediterranean: status, pressures, trends, and | 2014 |

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| Aftercare measures | Andres, P. Zapater, V. Pamplona, M. | Stabilization of motorway slopes with herbaceous cover, Catalonia, Spain. | 1996 |
| | Blondel, J., Aronson, J., Bodiou, J.Y. and Boeuf, G. | The Mediterranean region: biological diversity in space and time. | 2010 |
| Nurse plants | Padilla, FM. and Pugnaire, FI. | The role of nurse plants in the restoration of degraded environments. | 2006 |
| | Skousen, JG. Zipper, CE. | Reclamation Guidelines for Surface-Mined Land: Revegetation Species and Practices. | 2010 |
| | Zelnik, I. Šilc, U. Čarni, A. Košir, P. | Revegetation of motorway slopes using different seed mixtures. | 2010 |
| Water | Bochet, E. and García-Fayos, P. | Factors controlling vegetation establishment and water erosion on motorway slopes in Valencia, Spain. | 2004 |
| | Bochet, E. García-Fayos, P. Alborch, B. Tormo, J. | Soil water availability effects on seed germination account for species segregation in semiarid roadslopes. | 2007a |
| | Bochet, E. García-Fayos, P. Poesen, J. | Topographic thresholds for plant colonization on semi-arid eroded slopes. | 2009 |
| | Bochet, E. García-Fayos, P. Tormo, J. | How can we control erosion of roadslopes in semiarid mediterranean areas? Soil improvement and native plant establishment. | 2010a |
| | Cerdà, A. | Soil water erosion on road embankments in Eastern Spain. | 2007 |
| Cerdà, A. and García-Fayos, P. | The influence of slope angle on sediment, water and seed losses on badland landscapes. | 1997 |
|---|---|---|
| García-Fayos, P. García-Ventoso, B. Cerdà, A. | Limitations to plant establishment on eroded slopes in Southeastern Spain. | 2000 |
| García-Palacios, P. Soliveres, S. Maestre, FT. Escudero, A. Castillo-Monroy, AP. Valladares, F. | Dominant plant species modulate responses to hydroseeding, irrigation, and fertilization during the restoration of semi-arid motorway slopes. | 2010 |
| Josa, R. Jorba, M. Vallejo, VR. | Opencast mine restoration in a Mediterranean semi-arid environment: failure of some common practices. | 2012 |
| Tormo, J. Bochet, E. García-Fayo, P. | Is seed availability enough to ensure colonization success? An experimental study in road embankments. | 2006 |
| Vallone, M. Pipitone, F. Alleri, M. Febo, P. Catania, P. | Hydroseeding Application on Degraded Slopes in the Southern Mediterranean Area (Sicily). | 2013 |
| Wainwright, J. | Anthropogenic factors in the degradation of semi-arid regions: a prehistoric case study in Southern France. | 1994 |
| Albaladejo Montoro, J. Alvarez Rogel, J. Querejeta, J. | Three hydro-seeding revegetation techniques for soil erosion control on anthropic steep slopes. | 2000 |
| Balaguer, L. | Las limitaciones de la restauración de la cubierta vegetal. | 2002 |

Soil addition
| Author(s) | Title and Details |
|-----------|------------------|
| Bochet, E. and García-Fayos, P. | Factors controlling vegetation establishment and water erosion on motorway slopes in Valencia, Spain. 2004 |
| Brofas, G. Mantakas, G. Tsagari, K. Stefanakis, M. Varelides, C. | Effectiveness of cellulose, straw and binding materials for mining spoils revegetation by hydroseeding, in Central Greece. 2007 |
| Gomez, JA. Rodríguez, A. Viedma, A. Contreras, V. Vanwalleghem, T. Taguas, EV. Giráldez, JV. | Evaluation of different techniques for erosion control on different roadcuts in its first year of implantation. 2014 |
| Hallock, BG. Power, A. Rein, S. Curto, M. Scharff, M. | Analysis of Compost Treatments to Establish Shrubs and Improve Water Quality. 2006 |
| Jimenez, MD. Ruiz-Capillas, P. Mola, I. Pérez-Corona, E. Casado, MA. Balaguer, L. | Soil development at the roadside: a case study of a novel ecosystem. 2013 |
| Merlin, G. Di Gioia, L. Goddon, C. | Comparative study of the capacity of germination and adhesion of various hydrocolloids used for revegetalization by hydroseeding. 1999 |
| Moreno de las Heras, M. Nicolau, JM. Espigares, T. | Vegetation succession in reclaimed coal-mining slopes in a Mediterranean-dry environment. 2008 |
| Rivera, D. Jáuregui, BM. Peco, B. | The fate of herbaceous seeds during topsoil stockpiling: restoration potential of seed banks. 2012 |
| Seed type/competition/inoculation/aqueous solutions | Microenviroment | |  |
|----------------------------------------------------|-----------------|---|---|
| Simón-Torres, M. del Moral-Torres, F. de Haro-Lozano, S. Gómez-Mercado, F. | Restoration of dump deposits from quarries in a Mediterranean climate using marble industry waste. | 2014 | |
| Tormo, J. Bochet, E. García-Fayos, P. | Roadfill Revegetation in Semiarid Mediterranean Environments. Part II: Topsoiling, Species Selection, and Hydroseeding. | 2007 | |
| Elmarsdottir, A. Aradottir, AL. Trlica, MJ. | Microsite availability and establishment of native species on degraded and reclaimed sites. | 2003 | |
| Tormo, J. Bochet, E. García-Fayos, P. | Is seed availability enough to ensure colonization success? An experimental study in road embankments. | 2006 | |
| Andres, P. and Jorba, M. | Mitigation strategies in some motorway embankments (Catalonia, Spain). | 2000 | |
| Begon, M., Harper, J.L. & Townsend, C.R. | Ecology: From Individuals to Ecosystems. | 1996 | |
| Bochet, E. Tormo, J. García-Fayos, P. | Native species for roadslope revegetation: selection, validation, and cost effectiveness. | 2010b | |
| Boscutti, F. Vianello, A. Bozzato, F. Casolo, V. | Vegetation structure, species life span, and exotic status elucidate plant succession in a limestone quarry reclamation. | 2016 | |
| Bradshaw, A.D. | The reclamation of derelict land and the ecology of ecosystems. | 1987 | |
| Authors                                      | Title                                                                                                           | Year |
|----------------------------------------------|-----------------------------------------------------------------------------------------------------------------|------|
| Catania, P. Salvia, M. Vallone, M.          | Hydroseeding for revegetation in a semi-arid Mediterranean environment. In Structures and Environmental Technologies. | 2012 |
| Clemente, AS. Moedas, AR. Oliveira, G. Martins-Loução, MA. Correia, O. | Effect of hydroseeding components on the germination of Mediterranean native plant species.                   | 2016 |
| Engelbrecht, M. and García-Fayos, P.        | Mucilage secretion by seeds doubles the chance to escape removal by ants.                                       | 2012 |
| Estaun, V. Vicente, S. Calvet, C. Camprubi, A. Busquets, M. | Integration of arbuscular mycorrhiza inoculation in hydroseeding technology: effects on plant growth and inter-species competition. | 2007 |
| González-Alday, J. Marrs, RH. Martínez-Ruíz, C. | Soil seed bank formation during early revegetation after hydroseeding in reclaimed coal wastes.                 | 2009 |
| Khater, C. and Martin, A.                   | Application of restoration ecology principles to the practice of limestone quarry rehabilitation in Lebanon.    | 2007 |
| Khater, C. Martin, A. Maillet, J.           | Spontaneous vegetation dynamics and restoration prospects for limestone quarries in Lebanon.                    | 2003 |
| Maestre, FT. Bowker, MA. Cantón, Y. Castillo-Monroy, AP. Cortina, J. Escolar, C. Escudero, A. Lázaro, R. Martínez, I. | Ecology and functional roles of biological soil crusts in semi-arid ecosystems of Spain.                      | 2011 |
| Authors                                      | Title                                                                 | Year |
|----------------------------------------------|-----------------------------------------------------------------------|------|
| Martin, A. Khater, C. Mineau, H. Puech, S.  | Rehabilitation ecology by revegetation. Approach and results from two Mediterranean countries. | 2002 |
| Martínez-Ruiz, C. Fernandez-Santos, B. Putwain, PD. Fernández-Gómez, MJ. | Natural and man-induced revegetation on mining wastes: changes in the floristic composition during early succession. | 2007 |
| Matesanz, S. and Valladares, F.              | Improving revegetation of gypsum slopes is not a simple matter of adding native species: Insights from a multispecies experiment. | 2007 |
| Merlin, G. Di Gioia, L. Goddon, C.           | Comparative study of the capacity of germination and adhesion of various hydrocolloids used for revegetalization by hydroseeding. | 1999 |
| Miller, RM. and Jastrow, DJ.                | The application of VA mycorrhizae to ecosystem restoration and reclamation. | 1992 |
| Navas, M. and Moreau-Richard, J.            | Can traits predict the competitive response of herbaceous Mediterranean species? | 2005 |
| Oliveira, G. Clemente, A. Nunes, A. Correia, O. | Limitations to recruitment of native species in hydroseeding mixtures. | 2013 |
| Oliveira, G. Clemente, A. Nunes, A. Correia, O. | Suitability and limitations of native species for seed mixtures to re-vegetate degraded areas. | 2014 |
| Oliveira, G. Nunes, A. Clemente, A. Correia, O. | Testing Germination of Species for Hydroseeding Degraded Mediterranean Areas. | 2012 |
| Peco, B. Ortega, M. Levassor, C. | Similarity between seed bank and vegetation in Mediterranean grassland: a predictive model. | 1998 |
| Pywell, R.F., Bullock, J.M., Roy, D.B., Warman, L.I.Z., Walker, K.J. and Rothery, P | Plant traits as predictors of performance in ecological restoration. | 2003 |
| Steinfeld, DE. Riley, SA. Wilkinson, K M. Landis, TD. Riley, LE. | Roadside revegetation: an integrated approach to establishing native plants. | 2007 |
| Tormo, J. García-Fayos, P. Bochet, E. | Relative importance of plant traits and ecological filters in road embankment revegetation under semiarid Mediterranean conditions. | 2008 |
| Andres, P. Zapater, V. Pamplona, M. | Stabilization of motorway slopes with herbaceous cover, Catalonia, Spain. Restoration Ecology 4:51-60 | 1996 |
| Ballesteros, M. Cañadas, EM. Marrs, RH. Foronda, A. Martín-Peinado, FJ. Lorite, J. | Restoration of gypsicolous vegetation on quarry slopes: guidance for hydroseeding under contrasting inclination and aspect. | 2017 |
| Bochet, E. and García-Fayos, P. | Factors controlling vegetation establishment and water erosion on motorway slopes in Valencia. Spain. | 2004 |
| Bochet, E. García-Fayos, P. Poesen, J. | Topographic thresholds for plant colonization on semi-arid eroded slopes. | 2009 |
| Bochet, E. García-Fayos, P. Tormo, J. | Road slope revegetation in semiarid Mediterranean environments. Part I: seed | 2007b |
| Socio-economic factors | Dispersal and spontaneous colonization. | Cano, A. Navia, R. Amezaga, I. Montalvo, J. | Local topoclimate effect on short-term cut-slope reclamation success. | 2002 |
|------------------------|----------------------------------------|---------------------------------------------|-----------------------------------------------------------------|------|
|                        |                                        | Cerdà, A. and García-Fayos, P.              | The influence of slope angle on sediment, water and seed losses on badland landscapes. | 1997 |
|                        |                                        | Dubayah, R.C.                               | Modeling a solar radiation topoclimatology for Rio Grande River Basin. | 1994 |
|                        |                                        | García-Fayos, P. and Cerdà, A.             | Seed losses by surface wash in degraded Mediterranean environments. | 1997 |
|                        |                                        | González-Alday, J. Marrs, RH. Martínez-Ruiz, C. | The influence of aspect on the early growth dynamics of hydroseeded species in coal reclamation areas. | 2008 |
|                        |                                        | Bochet, E. Tormo, J. García-Fayos, P.      | Native species for roadslope revegetation: selection, validation, and cost effectiveness. | 2010b |
|                        |                                        | Fenianos, J. Khater, C. Viglione, J. Brouillet, D. | Bridging nature and human priorities in ecological rehabilitation projects - a show case from Mediterranean environment - Qattine, Lebanon. | 2017 |
|                        |                                        | Martin, A. Khater, C. Mineau, H. Puech, S. | Rehabilitation ecology by revegetation. Approach and results from two Mediterranean countries. | 2002 |
RESULTS

Hydroseeding techniques and their limitations

In semi-arid Mediterranean climates, hydroseeding has yielded poor results in plant performance (Matesanz et al., 2006). These results could be due to a lack of sufficient knowledge about the success of hyrdoseeded species and the performance of native species (Bochet and García-Fayos, 2004). Understanding the response of those established species is critical for successful ecosystem restoration, and improving seed mixtures (González-Alday et al., 2008).

Several factors affect hydroseeding successes or failures. Those factors can be grouped under abiotic factors or biotic factors (Table 2).

Table 2. Main factors extracted from the literature review that might be affecting the success or failure of the hydroseeding procedure in a semi-arid Mediterranean environment.

| ABIOTIC FACTORS | BIOTIC FACTORS | OTHER FACTORS |
|-----------------|----------------|---------------|
| Natural Environmental | Human-Induced | Natural Environmental | Human-Induced | Starting Conditions |
| Site Topography and Properties: | Direct Hydroseeding Practices: | Perils Affecting Seeds: | Seeds Used: |
| - Steepness & angle | - Aqueous Hydroseeding type and properties | - Weed competition | - Type |
| - Aspect | - Intervention season | - Seed predation | - Availability & germination difficulties |
| Soil Physical Characteristics: | Varied Cultural Practices: | Seed Interaction: | Seed Interaction: |
| - Soil present/absent | - Supplemental irrigation | - Interspecific seed competition | - Type |
| - Microenvironment effect | - Soil addition & amending | - Nurse plants | - Availability & germination difficulties |
| Water Effect: | - Mulching | - Mycorrhizal inoculation | - Initial Status of Intervention Area |
| - Water availability | | | Cost Social Factor |
| - Erosion | | | |

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Starting conditions are the existing conditions ranging from abandoned semi-natural environments to areas intensively used as cropland or heavily disturbed places such as quarries and mines (Hölzel et al., 2012). Although it is a very important aspect, this topic will not be covered in this review because it is out of scope when discussing hydroseeding pros and cons.

Abiotic factors affecting hydroseeding

Numerous abiotic factors might affect the hydroseeding end result those can either be natural-environmental factors or human-influenced factors (Table 2). Those factors do not act alone and often interact with one another or with different biotic factors.

Table 3. Factors affecting hydroseeding results in a semi-arid Mediterranean environment (NA - Natural Abiotic factors affecting hydroseeding; HA - Human-induced Abiotic factors affecting hydroseeding; HB - Human-induced Biotic factors affecting hydroseeding).

| Variables         | Successes                                                                 | Failures                                                                 |
|-------------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Slope Steepness   | Slight to mild slope steepness - less than 45 degrees (NA)                 | Unmanaged steep slopes above 45 degrees (NA)                              |
|                   | Terracing slopes above 45 degrees (HA)                                     |                                                                          |
| Aspect / Solar radiation | North facing - Low levels of solar radiation (NA)              | South facing - High levels of solar radiation (NA)                        |
| Soil              | Presence of topsoil (conservation of microorganisms, seeds, and nutrients) (NA/HA) | Absence of topsoil (loss of microorganisms, seeds, and nutrients) (NA/HA) |
|                   | Presence of microenvironment: increased soil surface roughness (small rocks, aggregates) (NA/HA) |                                                                          |
|                   | Addition of topsoil or amendments (HA)                                     |                                                                          |
|                   | Mulching (synthetic or organic) (HA)                                      |                                                                          |
|                   | Mycorrhizal soil inoculation (HB)                                          |                                                                          |
| Water             | Water abundancy conditions: regular rainfall (NA) or supplemental irrigation (HA) at germination/seedling phase | Water-stressed conditions: absence / irregular rainfall (NA) or lack of irrigation (HA) at germination/seedling stage |
| Weeds             | Reduction of weed competition through appropriate selection of native seeds mixture (HB) | Commercial seeds (HB), non-native seeds (HB/NB), seed predation (NB), inappropriate species (HB), lack of |
| Seed choice       | Native (NB), competitive ability (NB), colonizing ability (NB), vegetative |                                                                          |
### Natural-environmental abiotic factors affecting hydroseeding

Natural-environmental abiotic factors are factors related to site topography, aspect, edaphic characteristics, and water availability. Topography and extreme environments can determine the success of a planting and restoration program (Bochet et al., 2009). Slope steepness, aspect, and type are all factors to consider in a harsh semi-arid Mediterranean climate. Because of low penetration and high runoff (Miyazaki et al., 1993), slopes with steep angles have intense water insufficiency, which leads to very low plant cover, accentuating the difficulty of re-vegetating them (Andre`s et al., 1996).

Studies on motorway slopes in Catalonia-Spain concluded that hydroseeding was unsuitable for slope stabilization of road cuts near, or above, 45 degrees. The causes of failure include the probability of seeds moving downhill, with or without water (Cerdà and García-Fayos, 1997; García-Fayos and Cerdà, 1997). Even at lower steepness, on slope angles greater than 27–32 degrees, seed establishment is hindered by downward dragging (Bochet and García-Fayos, 2004). A study conducted in Malaga-Spain assessed whether hydroseeding techniques had any significance to contribute to species richness and vegetation cover by acting as starters or facilitators in the establishment of plants, and eventually checking their fate after the ecosystem has been restored. Results revealed that hydroseeding did not prove successful and the vegetation establishment on embankments was mainly from local seed bank and dispersal from the surrounding area (Bochet et al., 2007b). It concluded that hydroseeding is not needed in the presence of favorable conditions such as suitable climate and slope angle (Matesanz et al., 2005). To improve hydroseeding success in steep slopes efforts need to focus on increasing surface roughness, terracing at regular intervals, or excavating to produce slope angles below 45 degrees (Bochet and García-Fayos, 2004). Another factor affecting hydroseeding is the slope aspect. Different slope aspects (N, E, S, or W) have various exposures to solar radiation. Bochet et al. (2009) studied the correlation between slope angle thresholds and slope aspect with respect to plant colonization of highly eroded slopes in a semi-arid area.
They observed that plant colonization started at higher slope angles on North-facing than on South-facing slopes. This difference in the colonization capacity is due to water availability which is controlled by the solar radiation received. Another study in northwestern Spain evaluated the solar radiation effect on short-term herbaceous plant establishment on roadcut slopes after hydroseeding. Results showed a significant coincident trend of decrease in plant density, biomass, plant cover, and seedling development along the SE–SW–S gradient (Cano et al., 2002). Additional studies revealed that vegetation establishment was reduced considerably on South-facing slopes due to more severe conditions (Andre’s et al., 1996; Cano et al., 2002). Aspect influence on early growth dynamics of hydroseeded species in a coal reclamation mine showed that grasses dominated both Northern and Southern slopes, except during the summer on the Southern slope, with grass cover always more on North-facing compared to South-facing slopes (González-Alday et al., 2008). A Contradicting study of almost three years involved hydroseeding gypsicolous vegetation on quarry spoil slopes. The two tested slopes (10-15% vs. 60-65%) and two contrasting aspects (North vs. South) revealed that shallow and Southern slopes were more suitable compared to Northern and steep slopes where non-target species developed readily outcompeting target species (Ballesteros et al., 2017).

A third natural-environmental abiotic factor affecting hydroseeding is the site edaphic characteristic. Soil presence or its absence, erosion, and microclimate are all factors affecting hydroseeding results. Initial soil conditions are the main factor leading to vegetation succession in reclaimed slopes in Mediterranean dry environment (Moreno de las Heras et al., 2008). Preservation of removed topsoil from construction sites is a valuable resource for ecological restoration. Removed soil contains high concentrations of micro-organisms, nutrients (Rivera et al., 2012), native seeds, and organic matter. All those factors could enhance plant establishment, increasing hydroseeding success rates (Merlin et al., 1999; Balaguer, 2002).

With the water running over bare and crusted soils leading to seed removal (Mitchley et al., 1996), the erosion process in Mediterranean climates is an important factor affecting hydroseeding, operating in a catastrophic mode (Wainwright, 1994). A major objective of hydroseeding is to generally control water erosion and the mechanical stabilization of barren slopes (Bochet et al., 2010a). A study in Spain on bare road embankments under construction revealed that the effect of erosion was 30 times more than the vegetated ones (Cerdà, 2007).

As for the microclimate effect, several degraded Mediterranean sites have adverse microclimatic conditions. Such inappropriate microsites, along with water stress, will affect the seedling establishment and plant growth, leading to poor performance of native species in hydroseeding (Tormo et al., 2006). The microclimate established between soil particles and adjacent aggregates will allow partial seed burial enabling a greater chance
for successful seedling establishment. The presence of small rocks will also provide shade and shelter, improving the establishment of seedlings (Elmarsdottir et al., 2003).

Water availability is yet another significant natural-environmental abiotic factor affecting hydroseeding success. In a Mediterranean semi-arid climate, water availability is a main ecological driver that shapes vegetation (Bochet et al., 2009). Low and irregular distribution of rainfall is a key factor limiting plant growth (Zohary, 1973). Seed arrival to road embankments under Mediterranean climate conditions is not enough to ensure successful plant colonization (Tormo et al., 2006). A study on regolith slopes in Southeast Spain concluded that short-lived water availability and high salinity of the regolith seem to be the key factors limiting vegetation colonization (García-Fayos et al., 2000). Furthermore, recurrent droughts cause not only high rates of plant mortality but also the inability of some species to expand their populations in dry conditions (Cerdà and García-Fayos, 1997, García-Fayos and Cerdà, 1997). Moreover, during the seedling establishment stage, the differences in water availability could explain the very-low plant colonization success, and the differential ability of plant species to establish in badland slopes (García-Fayos et al., 2000).

**Human-influenced abiotic factors affecting hydroseeding**

Human-influenced abiotic factors are factors introduced or modified by direct human interferences aiming to influence hydroseeding outcomes. Described under either direct-hydroseeding practices, varied cultural practices, cost of application, or social factors.

A factor that could directly affect hydroseeding practices is the type of aqueous solution utilized. One study (Merlin et al., 1999) assessed the effectiveness of a group of colloidal substances (of natural and synthetic origin) used in hydroseeding spraying with respect to adhesion, germination, seed growth, and erosion limitations. Results revealed that the desired colloids should have several characteristics: fluidity, adhesion to seeds, enable effective seed germination, be free of material hazardous to the environment, limit erosion, help in restoration or establishment of biological and ecological functions, and is of a low cost.

Alternation of the slurry component is another factor affecting the hydroseeding success. A comparative study (Clemente et al., 2016) using germination tests assessed the effects of different slurry components (bacteria-based fertilizing agent, bio-stimulant, dye, and surfactant) on the performance of a dozen native species used in hydroseeding of quarry slopes. The components affected the germination of 4 out of 12 native species, favoring germination in 2 species (Thymus masticha & Cistus albibus) but delayed it in 2 other species (Bituminaria bituminosa & Helichrysum stoechas). The study concluded that the effect of slurry components on germination is species-specific; hence any used hydroseeding components should be adjusted to the sown species (Clemente et al., 2016).
Another study (Catania et al., 2012) evaluated commercially available seeds on a degraded artificial slope in a Southern Mediterranean area for the effectiveness of four different hydroseeding solutions. The study assessed total vegetation cover, hydroseeding vegetation cover, hydroseeding success index, and both the natural and hydroseeded vegetation height. In conclusion, the research revealed that success is conditioned by the type of the mixture components, with mixtures of equal terms earthworm humus and mulch providing the best results in terms of vegetation cover (Catania et al., 2012). The intervention season is another human-influenced abiotic factor affecting hydroseeding. Under semiarid Mediterranean conditions, hydroseeding timing appears to be a critical factor since climatic conditions following hydroseeding significantly affect species fate. Both climatic conditions and the selection of a suitable species capable to establish under water-stressed conditions should be considered since both factors are important in determining species performance in sowing (Tormo et al., 2008). If hydroseeding is to be performed out-of-season due to some strict schedule, efforts should focus on improving topsoil and microsite quality rather than increasing seed availability (Mola et al., 2011).

Various implemented cultural practices are other human-influenced abiotic factors affecting hydroseeding. Supplemental irrigation after hydroseeding is one such practice. In a semi-arid Mediterranean environment, the application of irrigation after hydroseeding is controversial, with some studies supporting it, whereas other studies highlight a negative role. Studies supporting supplemental irrigation reveal that water stress in a Mediterranean environment highly obstructs plant growth. Therefore, after hydroseeding, irrigation must be applied for a few months due to insufficient rain. This is especially essential since the brief durability of soil water availability largely determines germination successes (Bochet et al., 2007a; García-Fayos et al., 2000). Another study in Sicily showed that not only mulch and humus are needed, but also irrigation should be carried out during the dry period (Vallone et al., 2013). Other studies recommended the use of drought-tolerant plants along with a careful irrigation plan (Josa et al., 2012). However, other studies raised concerns about irrigation which might lead to the prevention of long-term vegetation establishment due to competition with spontaneous colonizers (García-Palacios et al., 2010). Another study targeting motorway slopes in Spain concluded that fast-growing species dominate the community, rendering irrigation and fertilization of little effect, indicating that hydroseeding neither had a strong impact on vegetation cover nor did it significantly decrease erosion rates of degraded sites in semi-arid Mediterranean environments (García-Palacios et al., 2010).

The addition of soil and/or amendments can also be another factor affecting hydroseeding outcomes. Topsoil spreading can improve soil texture, upsurges nutrient soil retention, decreases nutrient loss, reduce sediment runoff and facilitate quick development of dense vegetation cover (Jimenez et al., 2013). Topsoil addition prior to hydroseeding could be an important technique in roadfill revegetation in Mediterranean environments. This could be achieved through improving soil physical and chemical properties and also by providing a seed bank to assist spontaneous regeneration (Tormo et
A study showed that topsoiling followed by hydroseeding of a selected native seed mixture was the most effective treatment to control erosion on roadfills in terms of cost and benefit (Bochet et al., 2010b). Another study, assessing quarry restoration, evaluated the contribution of a 30 cm topsoil layer above marble sludge (a material with high water retaining capacity) before hydroseeding. The results indicated an increase in slope water storing capacity, significantly increasing biomass (Simón-Torres et al., 2014). Added topsoil low in organic matter, Fe and Mn, will limit vegetation establishment and development (Bochet and García-Fayos, 2004), therefore, mixing compost with the soil could improve germination of native seeds (Hallock et al., 2006).

Mulching is another implemented cultural practice. Mulches and organic amendments can promote seed burial, germination, and establishment, especially if dry soil conditions prevailed (Roberts and Bradshaw, 1985). A study conducted in the Giona Mountain-Greece examined the effectiveness of hydroseeding combined with varied materials. Results showed that hydroseeding alone leads to poor results, but when combined with tilling and mulching, it created satisfactory vegetation cover from the first year after application (Brofas et al., 2007). Mulching could also improve the odds of hydroseeding steep slopes. One study in Cordoba- Spain tested the effectiveness of different mulches (vegetal mulch, humic acids, vegetal mulch with humic acids, and control) on steep slopes. Hydroseeding with the combination of plant mulch and humic acids significantly reduced soil runoff up to 98.5 percent. This result may be attributed to the combined effect of the protection against raindrop impact and improvement to soil structure brought by organic amendments (Albaladejo et al., 2000). Even in some cases, the total replacement of hydroseeding by spreading of a thick compost blanket (pellet form) could enormously benefit seeds germination, because of matting effect, enabling them to withstand harsher and more intensive rainfalls compared to hydroseeding (Tyler, 2003). Gomez et al. (2014) evaluated the effect of three different mats paralleled with hydroseeding for controlling erosion under Mediterranean conditions. The mats used were: Organic mats (made of coconut or esparto grass fiber), synthetic net mats, and synthetic 3D-net mats. Significant erosion control was achieved using different erosion mats combined with hydroseeding, versus control, but showed no clear differences among the diverse matting materials during one year (Gomez et al., 2014).

Cost is yet another factor affecting the decision regarding whether to implement hydroseeding or not. A study compared the cost of different kinds of applications (broadcasting, drill, and hydroseeding). Results revealed that broadcasting cost ranged from $25 to $75 /hectare, drilling native seed cost range was $60 to $135 /hectare, and hydroseeding cost was $1,358 /hectare (Pawelek et al., 2015). A probable reason for the high cost of hydroseeding could be the market price of native seeds. Another study revealed that the prices of selected seed mixtures were 30 times more than that of commercial species, although the cost of relevant ecological advantages provided by the use of native species was only twice that of the commercial species based on cost-effectiveness assessment (Bochet et al., 2010b). Martin et al. (2002) compared the prices
(in USD/kg) amongst different kinds of seeds used for hydroseeding in the semi-arid Mediterranean environment. Results revealed a vast range in the price range. With prices varying from as low as 2 - 3.5 USD/kg for industrially produced species, to 80- 120 USD/Kg for native species (hand-harvested and collected near restoration area), 6- 25 USD/kg for common cultivated wild species, and between 50- 850 USD/kg for the difficult to collect and grow wild species. More demand for native species in restoration projects will probably encourage investing in native seed and plant production, ultimately leading to their abundance at more competitive prices (Bochet et al., 2010b).

**Biotic factors affecting hydroseeding**

Biotic factors could play a positive or negative role in the outcome of hydroseeding by affecting separately or collectively hydroseeding outcomes (Table 3). Also, both biotic and abiotic factors might interact altering the end result.

**Human-influenced biotic factors affecting hydroseeding**

Through the influence of the soil seed bank, seeds are considered one of the most important actors at the first stages of the restoration process, playing a fundamental role in the composition of future vegetation (Peco et al., 1998). Therefore, the choice of species in seed mixtures is vital when planning a restoration project. Possible guidelines for seed selecting could be, the ability of seeds to disperse, produce sufficient viable seeds, be competitive under local conditions, be of perennial nature, and have a high root/shoot ratio (Khater et al., 2003). Three- groups of seed species are used for hydroseeding: Commercial species, native seed species collected near the intervention area, and native seeds obtained from cultivated wild species (Martin et al., 2002). Commercial species are those plant seed species produced in vast amounts following international norms. Although the use of commercial grasses and legume seeds are probably the most prevalent hydroseeding roadside re-vegetation method (Steinfeld et al., 2007), they frequently give poor results from the very beginning (André’s and Jorba, 2000; Martínez-Ruiz et al., 2007). Extremely competitive forage grasses and legumes (ex: Lolium multiflorum, Vicia villosa, Festuca arundinacea, Medicago sativa, Onobrychis sativa, Agropyron cristatum, Melilotus officinalis) (Bochet et al., 2010b) are in most locations non-native seeds used for agriculture practices or lawn establishment. Choosing seeds that are not adapted to harsh climatic constraints, like those prevailing in semi-arid Mediterranean environments, will lead to failure (Martin et al., 2002), especially with long periods of drought and erosive rains (Bochet and García-Fayos, 2004). A study in West-Central Spain evaluated the influence of using commercial seed mixtures in hydroseeding to restore uranium mine wastes under semi-arid Mediterranean climate. Results confirmed the non-suitability of commercial species mixture, suggesting instead to use local seeds (Martínez-Ruiz et al., 2007). Commercial seed mixtures also give poor results regarding species richness and overall biomass. As the dominance of certain used species eventually takes over other spreading or native spontaneous ones (Tormo et al., 2008). Therefore,
careful assessment of the competitive interactions among commercial and native species is imperative when both seed types are intended for use in a mixture, else it can dramatically affect the outcome of hydroseeding (Matesanz and Valladares, 2007). Using inappropriate species might potentially hinder the establishment of autochthonous species, lead to low diversity in communities, and can even become an integral part of the seed bank causing long-term problems (González-Alday et al., 2009). The importance of using native species is becoming widely acknowledged, and restoration projects are gradually considering native species for hydroseeding mixtures (Matesanz and Valladares, 2007). Unfortunately, several problems hinder the use of native seeds for hydroseeding in a Mediterranean environment. Concerns such as the scarce availability of information about proper seed collection methods, handling, storage, germination requirements, and seedling culture (Clewell and Rieger, 1997) leads to the narrowing down of choices of seeds used mainly to three main criteria’s: ecological needs, agro-ecological constraints and economic feasibility (Khater and Martin, 2007). Odds could be enhanced through species selection, seeds pre-treatment, hydroseeding scheduling, and/or manipulation of seeding density and relative species proportion (Oliveira et al., 2012).

Interspecific seed competition is yet another human-influenced biotic factor affecting hydroseeding practices. The kind and percentage of different seeds in a mixture, proportions of native seed densities, varied morphological features, or growth rates are all factors that could affect the end result. Hence, co-seeded species that display more competitive growth traits should be added at a lower proportion (Oliveira et al., 2013). Native species cannot simply be included in re-vegetation ‘recipes’, since success depends on density and seedling characteristics of the other co-seeded species. Therefore, their early performances and morphology must be taken into account in the choice of seed mixtures used in restoration actions (Oliveira et al., 2014). Another factor highlighted in literature affecting hydroseeding is the “nurse plant syndrome”, defined as the positive influence of the adult plants on seedlings (Niering et al., 1963). The harsher the ecological circumstances, the stronger the facilitative effect of nurse plants (Padilla and Pugnaire, 2006). Fast-growing annual species acting as nurse plants may be included with seed mixes of perennial grasses and forbs, providing protection for slower establishing perennial species by creating shade for a few months after seeds are applied (Skousen and Zipper, 2010). In the semi-arid Mediterranean environment, nurse plants will ultimately decline fast since they can hardly survive such harsh climatic conditions (Zelnik et al., 2010), their residues decomposed by soil microorganisms and nutrients released back to be used by perennial plant species (Skousen and Zipper, 2010). By rapidly re-establishing vegetation cover, nurse plants can also control erosion, consequently suppressing annual weeds (Mitchley et al., 1996). Zelnik et al. (2010) observed that seed mixtures with nurse species accelerate succession on slopes during the initial years but delay the establishment of late-successional species from the adjacent target vegetation. Hence, recommending that the proportion of nurse species in seed mixtures not exceed 20%.
Mycorrhizal inoculation is another human-influenced biotic factor affecting hydroseeding. Its use, among other inoculants, in restoration actions was recommended for the positive effect on plant establishment, nutrient cycling, ecosystem sustainability (Miller and Jastrow, 1992), and improvement of root enhancement and root branching density - a desirable quality in degraded soils (Stokes et al., 2009). They could also help to stabilize soil surface and create the assortment needed to increase plant production (Maestre et al., 2011). One of the few studies using inoculum for hydroseeding in semi-arid Mediterranean climate had the objective of selecting an adequate fungus combination (Arbuscular Mycorrhizal Fungi - AMF inoculum), along with legumes and grasses native to the Mediterranean region. The experiment evaluated the implications on severely disturbed areas as well under controlled conditions (greenhouse trial). Results revealed that the establishment of a symbiotic relationship improves aboveground plant growth and increases the legumes/grasses ratio (both in the greenhouse and in the field) (E斯塔un et al., 2007). Another study by Brown et al. (1983) measured rhizobium viability in hydroseeding slurries by testing variation in the pH due to fertilizer addition. They concluded that phosphorus fertilizer as triple-superphosphate significantly reduced the pH leading to the loss of Rhizobium viability. The study concluded that Phosphorous addition should be in the form of diammonium Phosphate rather than triple Superphosphate, ensuring Rhizobial survival, and inoculation of legume seeds (Brown et al., 1983).

Natural-influenced biotic factors affecting hydroseeding

Several perils could impact the fate of the hydroseeded seeds in their intended location, such as weed competition and seed predation. Weed competition was highlighted through a study in a limestone quarry in North-Eastern Italy evaluating the effect of technical reclamation on the plant community (Boscutti et al., 2016). It concluded that different practices favoring native perennial species (e.g. appropriate seed mixtures, mowing, tree and shrub planting) could limit weed-control efforts and limit invasive species spread (Boscutti et al. 2016). Another study measuring the basal area of herbaceous Mediterranean species revealed that plants with a large basal area were least suppressed by competition, concluding that plants basal area could be used to predict the competitive ability of species performance (Navas & Moreau-Richard, 2005). Seed predation is another natural-influenced biotic factor affecting hydroseeding, achieved through grazing by animals such as birds, mammals, ants (Chambers and MacMahon, 1994), or even pathogens (Hulme, 1998). A study that analyzed different types of seeds, actively collected, as food items by ants showed that more than 50% of the experimental seeds that were glued to the ground with their own mucilage survived, compared to only 0–20 % of the control of seed survival after the same exposure time (Engelbrecht and García-Fayos, 2012).

Whereas most studies in literature addressed technical issues as barriers in hindering hydroseeding processes, very few articles (Fenianos et al., 2017; 2018)
highlighted social factors as issues affecting it. To successfully implement adapted environmental solutions, especially in ecological restoration projects, Fenianos et al. (2017, 2018) investigated possible contributions of cognitive resistance and the need to work on increasing acceptability for adopting new or non-traditional techniques. Using cognitive flexibility as a mixed approach with awareness-raising sessions positively increased the perception of test groups towards less traditional and more ecological rehabilitation concepts on quarries.

**DISCUSSION**

Initially developed for ski slopes and side road embankments in Northern European countries, hydroseeding as a restoration tool has shown considerable limitations in Mediterranean ecosystems. This review from the semi-arid Mediterranean context concludes that the practice of hydroseeding is faced with limited success. A review of the main biotic and abiotic factors as either natural or human-induced that might be affecting it revealed several limiting factors. Some of those factors are site topography and its properties (slope angle, aspect, and microclimates availability), edaphic factors and water availability, cultural practices, the types of seeds used and the interaction among them, and the different perils facing them. Better results can be achieved by incorporating various techniques, such as using nurse plants, ameliorating the soil and its microclimates, supplemental irrigation, the proper choice of seeds, regulating spraying medium, and seed inoculation. Environmental socio-cognitive psychology approaches might help to better convey and increase acceptability towards modified applications of Hydroseeding.

As a consequence, the limits of using hydroseeding as a restoration technique in a semi-arid Mediterranean environment calls for additional research efforts to sufficiently comprehend its pros and cons.

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