RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration
SER SOCIETY FOR ECOLOGICAL RESTORATION

REVIEW ARTICLE

Biodiversity and its restoration in limestone quarries: a review

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Abstract

Introduction: Limestone quarries impact natural areas, and they are spreading in relation to human population growth. Little is known about the impact of limestone quarries and their restoration on biodiversity.
Objectives: This review aims to provide an overview of how biodiversity is assessed in limestone quarries, how it impacts biodiversity, and the restoration practices applied after mining.
Methods: We reviewed the published literature, including a total of 140 studies.
Results: Very few studies were designed to include more than one quarry or different control areas. Few studies examined the role of quarries as open habitats during mining operations, while the majority focused on habitat restoration after excavation. Restoration can occur through active or natural processes. Although active restoration, such as soil amendments and planting, was preferred, natural processes may better support communities that resemble those inhabiting natural calcareous grasslands. Even natural recovery often requires active management. Most studies focused on plants and arthropods, with very few addressing vertebrates. The impact of dust emission was mainly analyzed on plants and lichens.
Conclusion: There is a significant knowledge gap regarding biodiversity in active quarries and limited data on animal communities. Restoration efforts should integrate both active and passive strategies, with improved monitoring programs and broader taxonomic coverage.

Implications for Practice: Limestone quarries can host significant biodiversity, including several threatened species, such as those inhabiting calcicolous ecosystems. These can be enhanced through targeted restoration, which should involve native and xerophilous plant species, allowing natural processes to begin the recovery process. However, successful regeneration requires mitigation of harsh environmental conditions and alien species colonization. It is crucial to investigate a broader range of quarries and include more natural control areas. Monitoring and conservation actions must also target vertebrates, soil fauna, and microbial communities, especially threatened and early successional habitat species, which often find refuge in these novel ecosystems. This could be achieved by creating targeted microhabitats and improving landscape connectivity to facilitate colonization. Incorporating a traits-based approach would further enhance understanding of the conservation value and ecological dynamics of these environments.

Key words: calcicolous habitat, cement quarry, extraction activities, impacts, limestone mines, restoration

Introduction

Quarrying has significant impacts on the environment (Souza & Sánchez, 2018). Large-scale habitat destruction, dust, noise, and vibration emissions have been listed as the major negative environmental impacts (Kumarasinghe et al., 2013). Large-scale habitat destruction, due to the removal of soil and exposure of bedrock is reported to be one of the most severe negative impacts of quarrying on biodiversity (Carabia-Sanz et al., 2024). Air pollution caused by the emission of particulate matter into the atmosphere from quarrying can also lead to severe sub-lethal effects on animals, for example, on butterflies (Piccini et al., 2023), or impact plant and animal growth (Kumarasinghe et al., 2013). Mining produces high levels of noise and vibration, disturbing animals and adversely affecting their behavior, with irreversible knock-on effects on ecosystems (Telea et al., 2019). The cumulative impact of habitat loss/degradation, dust, noise, and vibration makes the areas surrounding excavation sites unsuitable for many species, which contributes to the global biodiversity crisis (Lameed & Ayodele, 2010).

Cement is the fundamental material for the construction of human infrastructure, and it is essential for the economic development of any country. More than 4 billion tons of cement and clinker were produced in 2021, with China being the world's largest producer (55%), while in Europe (EU27) 182.5 million

Author contributions: LD, GA, IP, MC research conceptualization; LD, GA, IP, MC methodology definition; LD, GA, IP, MC formal analysis and investigation; LD, IP, MC original draft preparation; LD, GA, IP, MC revision and editing.

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doi: 10.1111/rec.70255
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.70255/suppinfo

tons have been produced (CEMBUREAU, 2022). Due to the increasing growth of the human population and the consequent expansion of urban areas, the demand for cement and other building materials will become even higher, with a consequent increase in sites that will be dedicated to the extraction of materials needed for cement production (Cao et al., 2017).

These open-pit quarries are located in limestone and karst soils. The unique conditions of the landscapes which develop on these soils lead to the evolution of highly specialized species found nowhere else. Indeed, these environments host a huge diversity of endemic species, including vertebrates (Grismer et al., 2013), invertebrates (Osiele et al., 2022), and plants (Kiew et al., 2019). The proportion of endemic species within the community reaches high levels, ranging from 15% to over 60% (Clements et al., 2006). However, these environments are fragile and susceptible to external disturbances; indeed, the limestone and karst environments are precipitously declining, mainly due to mining for cement production (Clements et al., 2006). Several authors agree that there is an urgent need to halt the decline of the biodiversity associated with these habitats by intensifying conservation actions and environmental restoration (Kiew et al., 2019; Osiele et al., 2022).

The most common technique for limestone extraction involves open-pit mining with the creation of benches, slopes and terraces (Nováková & Šťastná, 2014). Besides the adverse effects of limestone mining—the harshest being calcicolous habitat loss—open-pit limestone quarries can lead to the creation of unique new habitats, characterized by bare rock and sparse vegetation with limited water availability. These industrial sites, also in response to specific restoration/management actions implemented, can be colonized by diverse plant and animal communities dominated by xerophilic and pioneer species that can tolerate harsh conditions, such as drought-resistant grasses and shrubs (Tropek et al., 2010). The settlement of these new communities can partly compensate for the loss of natural and semi-natural calcicolous ecosystems (Hula & Šťastná, 2010a).

Despite being a global issue of critical relevance for biodiversity conservation and restoration, the effects of cement quarries on biodiversity were irregularly assessed. The scientific literature on this topic is still unevenly distributed across taxa and regions, and this hampers the adoption of more sustainable practices to reduce these impacts. The purpose of this study is to systematically review: (1) how biodiversity is assessed in limestone quarries; (2) how cement quarrying impacts biodiversity; and (3) how restoration practices are conducted (both naturally and artificially) in these industrial sites after mining activities. The results of our review will be useful in developing strict regulations and guidelines not only that could help stakeholders to balance mining needs and environmental conservation but also to improve restoration practices after quarry abandonment.

Methods

We performed a systematic review including all databases incorporated within the Web of Science (accessed on 20 February 2025). The research employed a query with a series of combinations with increasing specificity, encompassing all the major and larger groups of living organisms:

("Limestone quarr*," "Cement quarr*," "Limestone min*") AND ("Biodiversity," Invertebrate*, "Vertebrate*," "Arthropod*," "Insect*," "Mammal*," "Avian*," "Bird*," "Amphibian*," "Reptile*," "Vegeta*").

The results obtained from the queries were manually examined and processed following the PRISMA methodology (Page et al., 2021). All articles that did not meet the following inclusion criteria were discarded: (1) studies conducted within or nearby limestone quarries or cement factories; (2) studies that assessed biodiversity or species ecology in these sites; (3) studies that quantified potential negative or positive impacts of limestone quarry activity on biodiversity at all levels in living organisms; (4) studies in English and peer-reviewed. Furthermore, we discarded articles published in journals not pertinent to our research focus (e.g. medicine, literature or paleontology).

The queries initially provided 828 results (Fig. 1), after removing duplicates and papers from journals from disciplines not relevant to our research, the remaining articles were scrutinized by carefully examining the title, abstract, and full text. After applying the inclusion criteria, we retained 140 papers (Fig. 1).

From each study, we extracted descriptive data on: (1) year of publication; (2) geographic origin; (3) general work aim; (4) taxonomic group(s) addressed; (5) taxonomic level considered; (6) ongoing activity: active or restored quarry; (7) the addition of amendment/amelioration in the restoration processes; (8) if the restoration process is achieved artificially or naturally; (9) the inclusion of control area(s); (10) the inclusion of threat or functional categories (Tables S1–S4).

We found three main aim categories: "Biodiversity in quarries," encompasses studies that monitored and quantified biodiversity within and around extraction sites, including biodiversity inventories or studies on the ecology of species inhabiting these areas; "Quarry impacts on biodiversity" consists of studies that measure the effects of quarrying activities on living organisms, including one or more impacts described above; "Quarry restoration" includes studies that focus on understanding the dynamics behind the restoration of quarry sites, including both natural and artificial methods of habitat restoration, aiming to provide insights into effective rehabilitation practices.

Results and Discussion

General Overview

The first paper was published in 1993; subsequently, a positive trend is evident in the number of published papers over the years (Fig. 2A). Almost 50% of the total articles have been published in the last decade, with a mean of 6.5 papers published per year. The papers were included in 89 different journals (Table S5).

The geographical distribution of studies reveals a significant number in Europe (Fig. 2C), which accounts for 73% of the overall publications. Several countries with an important mining

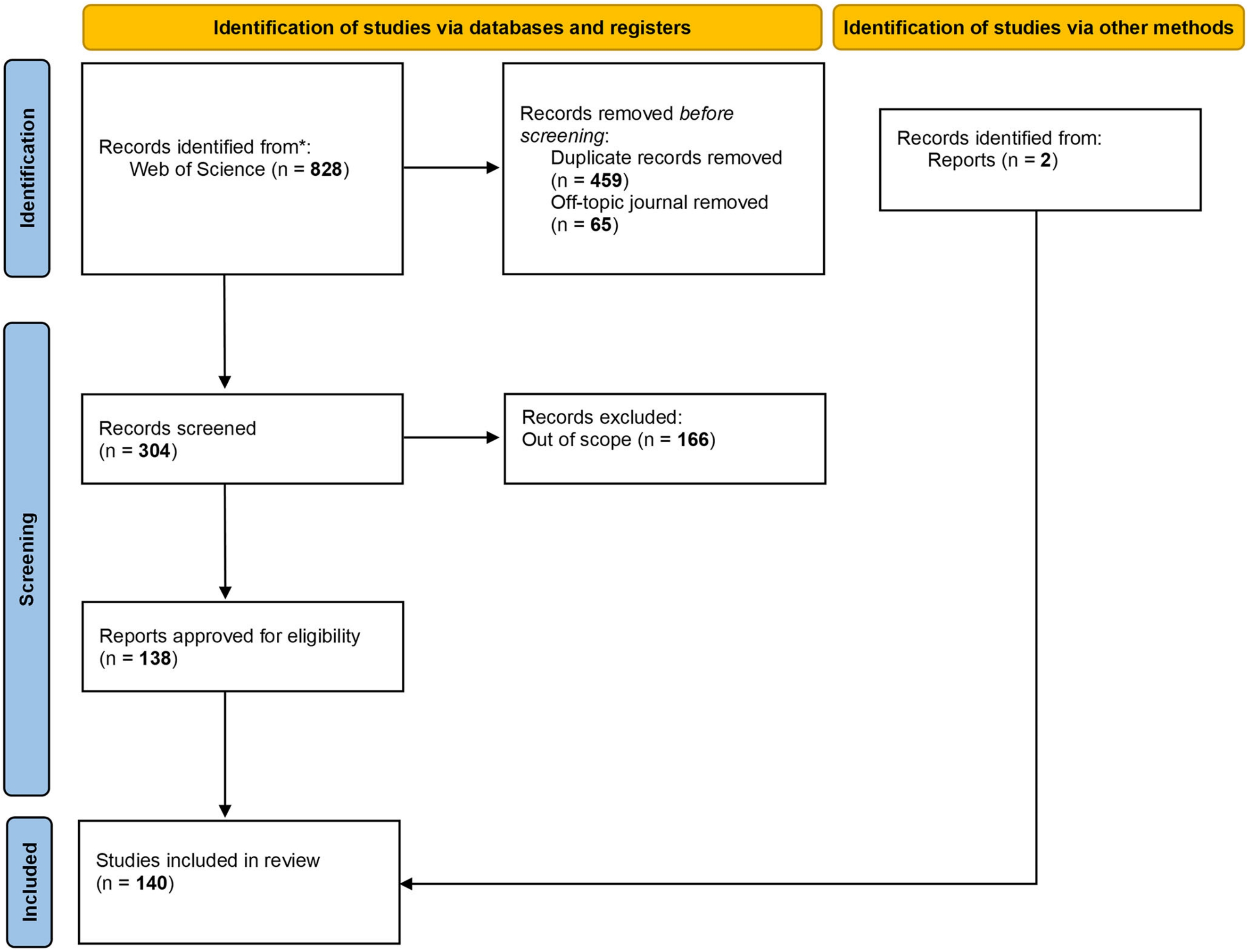

Figure 1. PRISMA flow chart showing the steps of data collection and data screening for this review. All the papers included in this review ($N = 140$), but not cited, are provided in the Supporting Information.

history are underrepresented, in particular in Central and South America and Africa. This constitutes a potential knowledge gap, which is harshened by the fact that these regions host an important share of the global biodiversity, and consequently, the potential impacts of limestone quarrying could be overlooked.

Fifty percent of the studies focused on "quarry restoration" ($N = 72$); in contrast, "quarry impacts on biodiversity" ($N = 9$) and "biodiversity in quarries" ($N = 51$) were represented by a lower number of studies (Fig. 2B). Generally, plants were the most studied taxonomic group (55% of the total), while studies focused on faunal groups represent a minor part of our collection, with invertebrates being the most studied group (23%). This reflects the taxonomic representation of the total number of studies, with the majority of these focused on the kingdom level ($N = 61$), species level ($N = 22$) and mixed taxonomic level ($N = 21$). Ninety-five out of 140 studies (68%) focused on restored sites that have completed their extractive activities, whereas 20 (14.2%) regarded active sites. Fourteen out of 140 papers (10%) had a more comprehensive approach by considering both active and restored sites, while a very small portion of the research did not specify the type of site under study ($N = 11$). Regarding studies focused on sites under restoration, 28 included soil amelioration, such as various types of amendment, NPK fertilizer, and so forth. Regarding the quarry restoration group, the majority of studies addressed technical restoration processes ($N = 56$), while much less focused on natural restoration ($N = 14$). The majority of the studies did not include any control areas/sampling points ($N = 75$) or any functional traits ($N = 73$) and threat categories ($N = 104$).

Biodiversity in Quarries

Both active and restored limestone quarries, often perceived as barren and inhospitable habitats, could be unique ecosystems that harbor remarkable biodiversity (Duco et al., 2021; Table S2). These environments, characterized by nutrient-poor substrates and harsh conditions, are the habitat of numerous endemics and specialized species that have adapted to thrive in such challenging habitats (Benes et al., 2003). Hence, they can

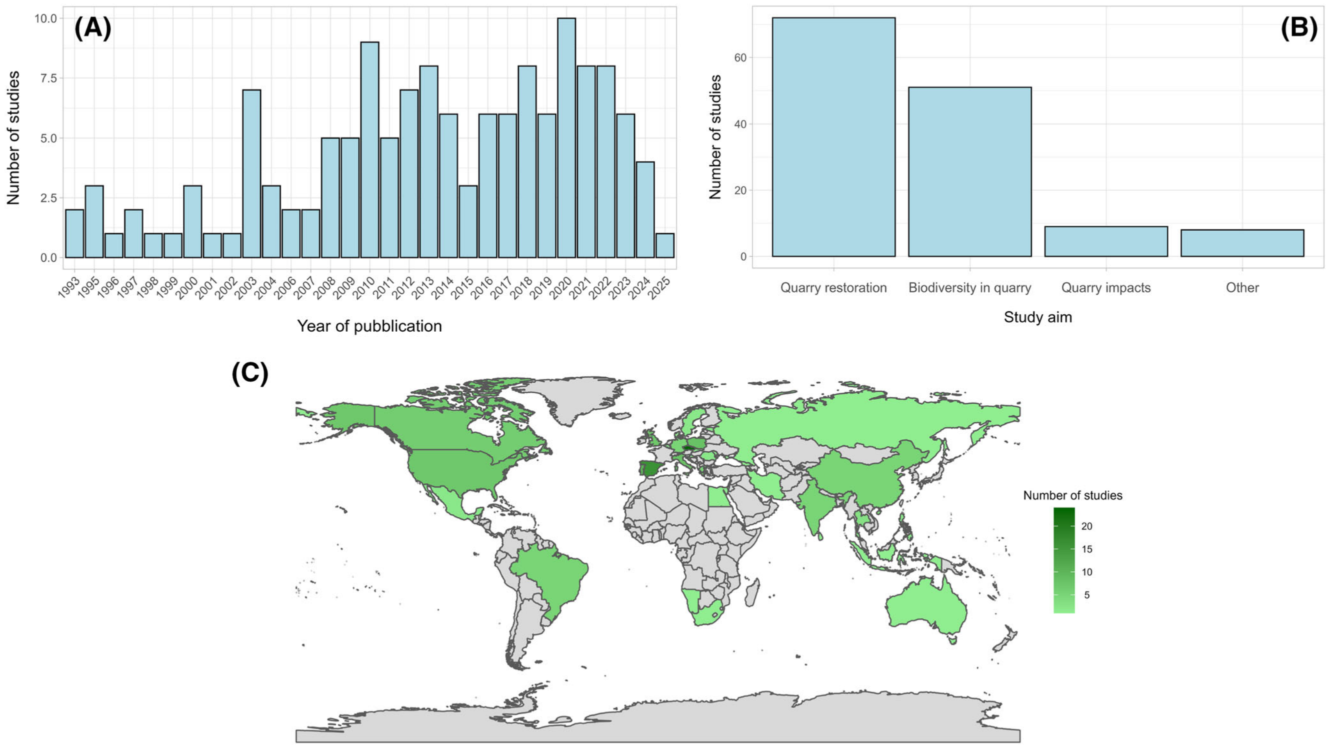

Figure 2. General data overview: (A) temporal trend of published papers; (B) number of articles according to their focus; (C) geographical distribution of the papers analyzed.

act as surrogates of natural calcareous habitats for all those xerophilous species which are increasingly threatened by human activities (Krauss et al., 2009). This highlights the dual role of open-pit quarries as both industrial sites and potential conservation areas for diverse ecological communities, similarly to what has been reported for sand and gravel pits, as they all create early successional and nutrient-poor habitats suitable for a variety of specialist and often endangered species (Řehounková & Prach, 2008; Heneberg et al., 2013).

Among animals, insects stand out as the most studied zoological group (10% of the total; Fig. 3). This suggests that insects are considered key indicators of biodiversity in these environments. The most addressed taxonomic groups among insects were Carabids ($N = 4$) and wild bees ($N = 4$). Lepidopterans accounted for two studies focusing on individual species or species complex (Beneš et al., 2003; Münsch & Fartmann, 2022) and one study examining the entire Lepidoptera community (Fig. 4). The lack of studies on other insects of xerothermic environments, such as other beetle orders, ants, orthopterans, and other pollinators, highlights a significant gap in research, which precludes a comprehensive understanding of biodiversity and ecosystem functioning in quarry habitats. Addressing these gaps would provide a more comprehensive view of the ecological dynamics within and around cement quarries, aiding in the development of effective conservation and management strategies.

In general, plant studies ($N = 14$) aimed to describe and characterize the flora within abandoned quarries, including data on community composition (e.g. Jasprica et al., 2018), genetic variation (Buryová & Hradílek, 2006), and functional traits (Frenedozo, 2004).

Twenty-eight studies (20% of the total) included functional, ecological and life history traits of the investigated species, such as reproductive strategies, growth rates, dispersal mechanisms, and habitat preferences. The majority of studies investigated these traits in invertebrate surveys, mostly considering arthropods, finding contrasting results even considering the same taxon. Indeed, quarries have been shown to attract spider specialists of early successional habitats, which are increasingly threatened worldwide (Tropek & Konvicka, 2008). In contrast, other studies found a high number of spider species that thrive in mature and stable-climax habitats (Hula & Šťastná, 2010b). Limestone quarries harbor not only rare spider species of rocky habitats but also generalist beetles (Tropek et al., 2008) and generalist odonates (Bobrek, 2020). Similarly, the quarry environment is predominantly inhabited by widespread carabid species that prefer open habitats. Furthermore, regarding habitat preferences, species requiring unshaded habitats and those indifferent to shading were primarily found on the quarry terraces and outskirts, with no species of shaded habitats reported (Novotná & Šťastná, 2012). Moreover, xerothermophilous carabids found refuge mainly in the marginal sites of the quarry (Nováková & Šťastná, 2014). Solitary hymenoptera were more affected by the reduction of suitable areas (due to quarry activities) compared to social bees (Krauss et al., 2009). Additionally, the overall species richness of particularly threatened and pollen

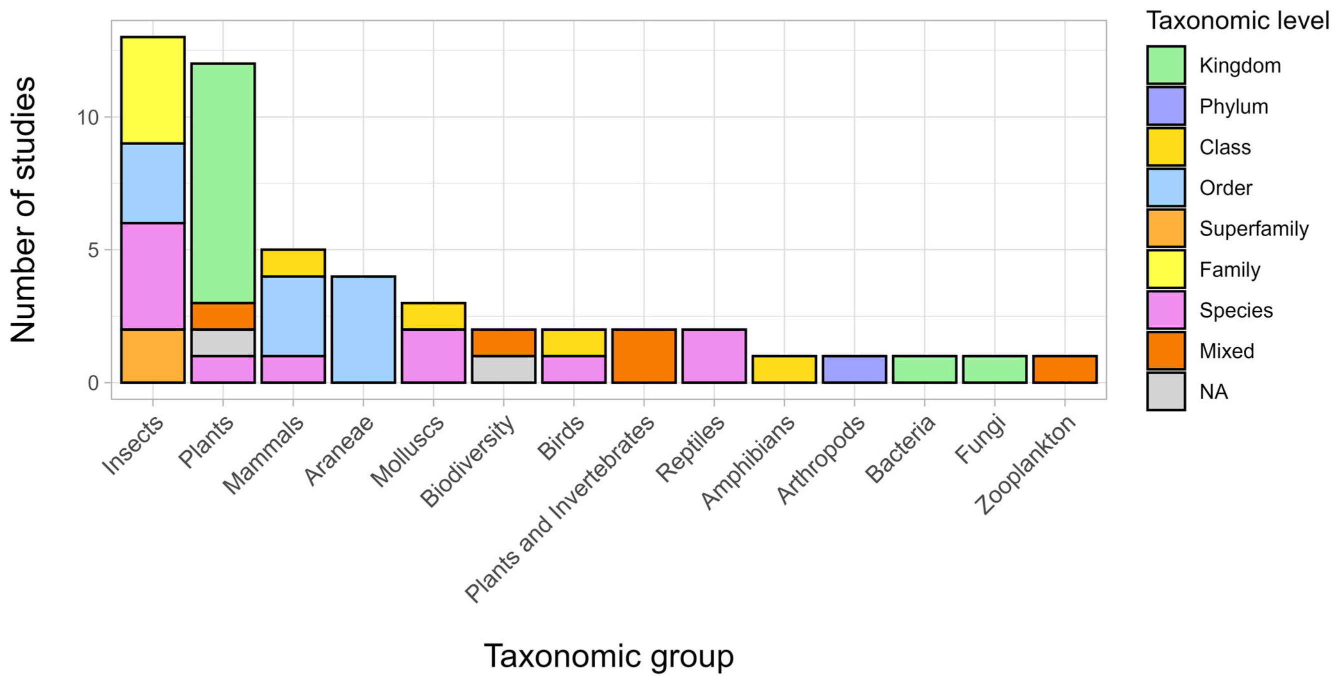

Figure 3. Taxonomic groups addressed in 51 studies focused on quarry biodiversity assessment. Different colors show the taxonomic level at which each study was conducted. Only the specific taxonomic group addressed in the main text was added in our data. Hierarchically nested taxa (e.g. Arthropoda and Insecta or Araneae) are treated as separate categories, to better reflect the taxonomic resolution reported in the studies.

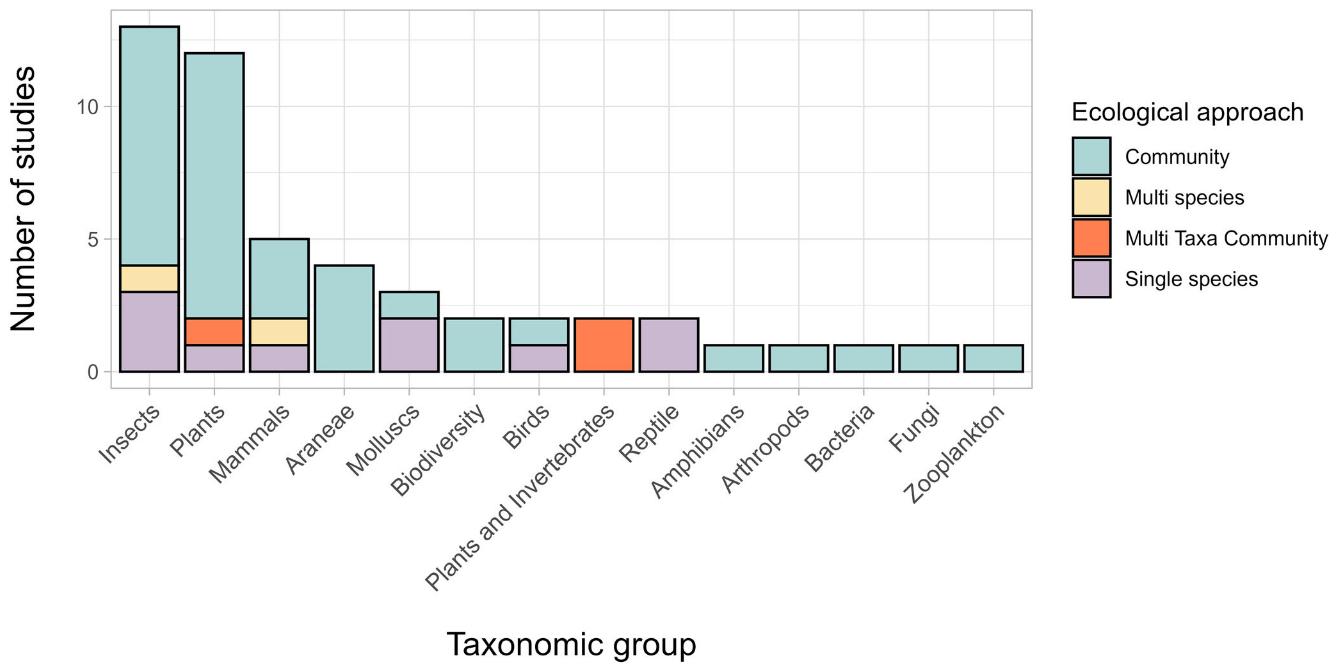

Figure 4. Ecological approach addressed in studies on quarry biodiversity across different taxa ($N = 51$). Different colors show the ecological approach adopted in each study. *Multi species* means that multiple species were considered without adopting a community approach; *Multi Taxa Community* means that multiple communities of different taxa were considered. *Biodiversity* is used when both plant and animal communities were considered together. Hierarchically nested taxa (e.g. Arthropoda and Insecta or Araneae) are treated as separate categories, to better reflect the taxonomic resolution reported in the studies.

specialist bees was favored in quarry environments (Kettermann et al., 2022). The number of xerophilous and sedentary butterfly species was high in small suitable parts of young active quarries and those adjacent to warm steppe grasslands (Benes et al., 2003). Considering vertebrates, the quarry environment is inhabited by generalist and disturbance-tolerant bird and mammal species of low conservation concern (Leiner & Silva, 2012; Duco et al., 2021).

Habitat preferences and ecological traits provide insights into how species interact with their environment, being strictly connected with its functionality (Schmitz et al., 2015). This information is essential for predicting how species will respond to changes in their habitat, such as those caused by quarrying activities. For instance, species with specific habitat requirements or limited dispersal abilities may be more vulnerable to habitat fragmentation and degradation, especially in industrial sites such as limestone quarries (Piccini et al., 2024).

Methodological Approaches to Address Biodiversity in Limestone Quarries

In general, all 140 studies included in this review, regardless of their different objectives, investigated biodiversity from various perspectives and with different methodologies. Approximately 53% of the studies did not include control areas or plots, and it should be noted that most of those that incorporated controls were focused on quarry restoration experiments. Furthermore, 74% of the studies have not accounted for the conservation status of the species under investigation. This omission could be largely attributed to the nature of the studies, which predominantly involved restoration efforts with a limited number of organisms serving as bioindicators or active agents in the restoration process. Additionally, 52% of the studies failed to include functional and ecological traits of the studied species, and 53% of the studies were conducted on a single quarry. This concentration on single sites is often a result of the experimental design implemented. Indeed, nearly all restoration experiments have focused on a single quarry, which may restrict the extension of the findings across different ecological contexts and quarry environments. However, from a methodological perspective, the absence of control areas in most studies is a substantial limitation. To assess changes in biodiversity, it becomes challenging to attribute observed changes in biodiversity directly to the effects of the cement quarry or other environmental variables without control areas (Stephenson et al., 2022). In addition, the absence of baseline data on biodiversity before the initiation of the quarrying activity is a pervasive methodological limitation of all the studies addressed. The only data approximating pre-impact conditions are derived from studies monitoring modern expansions of existing quarry sites (e.g. Kumarasinghe et al., 2013). For most historical quarries, this data gap is an unavoidable legacy of their establishment long before mandatory Environmental Impact Assessments. Consequently, the effective baseline for restoration-focused studies is the active quarry itself, not a preceding natural ecosystem. Even remote sensing studies using indices like NDVI are restricted to the post-extraction period, as the operational history of these quarries (60–120 years) precedes the satellite era (Vorovencii, 2011).

Finally, future studies must incorporate threat categories or conservation statuses to ensure a comprehensive and effective approach to biodiversity conservation in limestone quarries. This will enhance the relevance and applicability of the research, ultimately contributing to better conservation outcomes (Regan et al., 2008).

Quarry Impacts on Biodiversity

Quarries reduce habitat availability and quality in the extraction site but also blasting and material transportation produce a large amount of fine and coarse dust and noise emission. For instance, blasting operations are a primary source of ground vibrations and noise with effects on fauna (Lameed & Ayodele, 2010). Furthermore, extensive extraction activities can cause profound hydrological alterations, including the drawdown of local water tables or generate contaminated leachates that impact connected wetlands and watercourses (Neri & Sánchez, 2010). Nevertheless, only 6% of the reviewed studies estimated the direct impact of cement extraction activities or cement production on organisms (Table S3). All these studies focused on analyzing and quantifying the effects of dust pollution demonstrating clear negative effects at all levels of ecological hierarchy (from species to community) and generally are primarily concentrated on plants and lichens ($N = 8$). The impact of dust pollution on vegetation is significant, with studies indicating a reduction in plant vegetative growth, cover, density, and species diversity (Hegazy, 1996). Species richness and cover of bryophytes are slightly positively affected by alkaline dust pollution, with the distance from quarries being a key parameter influencing communities; however, these effects are temporary and create new "artificial" communities (Degtjarenko et al., 2016). Moreover, altered bark pH and changed environmental conditions can create suitable habitats for rare lichens and diversify the local communities and support bioindicators (Marmor & Degtjarenko, 2014). The distribution of lichens on trees is the main signal of dust contamination effects near limestone quarries (Paoli et al., 2014).

Dust accumulation influences both vegetation and seed banks, reducing productivity and depleting the soil seed bank. The absence of regeneration in the most polluted sites indicates that cement dust prevents the establishment of both local and invasive species (Hegazy, 1996). Recovery occurs once limestone extraction ceases and is accelerated by rainfall, which removes dust from leaves and stimulates new growth (Van Heerden et al., 2007).

Moreover, dust pollution generated by limestone mining and cement factories reduces the densities of Collembola and Acarina in the soil of polluted areas (Stancu, 2012).

Studies on the impact on animals of other disrupting factors on animals, such as noise and vibration, are lacking. Therefore, it is crucial to study the effects at the community level to gain a more comprehensive understanding of how the quarry activities impact biodiversity.

Quarry Restoration

Most studies pertained to the "Quarry restoration" category (Table S1). This group encompasses all processes and methodologies aimed at restoring and enhancing sites that have been degraded. Quarrying severely impacts calcareous ecosystems and their associated biodiversity (Clements et al., 2006). The restoration of these environments can be achieved either through a series of active human-made operations ("active restoration"; Prach & Tolvanen, 2016), or through the spontaneous secondary succession of vegetation ("passive restoration"), which over many years develops into a calcareous forest environment.

Active Restoration. This type of action may include the simple addition of fertile topsoil, as well as the sowing and planting of seeds and trees suitable for these extreme environments, in which the soil and associated nutrients are severely degraded (Prach & Tolvanen, 2016). Generally, active restoration is often preferred due to its perceived benefits to improve the landscape's appearance. However, the method used for post-mining restoration plays a critical role in determining how effectively different species can colonize the area (Tropek et al., 2010).

Our results also demonstrate this preference for active restoration. Seventy-nine percent ($N = 56$) of the studies have analyzed different active methods (from soil amelioration to simple planting) using several model organisms as indicators, from microbes to plants and animals. Seventeen percent of the total studies examined the dynamics of successful active restoration using an individual organism as a bioindicator, usually a plant or an arthropod. The results are mixed, depending primarily on the bioindicator considered or the type of restoration method implemented. For example, considering the plant community, the restoration success results are positive (Davis et al., 1993; Moreno-Peñaranda et al., 2004; Benetková et al., 2020) or negative considering long-term effects (Mexia et al., 2020). In general, the effectiveness of reclamation efforts in achieving target natural vegetation can be assessed using both vegetation structure and plant traits, with a decline in annual and alien species as vegetation reaches mature phases (Boscutti et al., 2017). Moreover, survival and growth of late-successional species increased with high levels of irrigation, while pioneer species showed the opposite trend (Soliveres et al., 2012). More specifically, 28 studies have carried out various treatments, from a single treatment of sewage sludge, fertilization, mycorrhization, gel polymers to retain water, up to a comparison between these different treatments. These methods are used mostly to improve the nutritional status of the soil and thus facilitate and expedite the restoration processes. The studies showed contrasting results, even using the same model organisms. Treatments were related to an improvement in the success of recovery, both in terms of vegetative cover and species diversity, as well as in the success of germination and growth of tree species (Moreno-Peñaranda et al., 2004; Carabassa et al., 2018) or even considering ecosystem services such as carbon sequestration and habitat function (Carabassa et al., 2020), but other studies showed that active treatments had no effect (Cohen-Fernández & Naeth, 2013a, 2013b; Soliveres et al., 2021). Beetles, at the species level, respond poorly or even negatively to active management (Eufrázio et al., 2020), while arthropod communities in general have greater diversity using a specific dose of sewage sludge (Andrés, 1999). Besides animal and plant communities, bacteria and fungi have been studied as indicators of rehabilitation success, demonstrating that artificial revegetation matched to a careful choice of plant species and the addition of amendments can positively influence bacterial communities (Luna et al., 2016; Alifragki et al., 2018). Active methods may also include the simple addition of topsoil from diverse sources: the transfer of the upper layer of fertile soil from arid forest environments could assist and improve recovery plans in these degraded environments. Using the plant community as an indicator, Ferreira and Vieira (2017), Benetková et al. (2020), and Soliveres et al. (2021) demonstrated that the upper layer speeds up the initial process of vegetation development. Also, biotic and abiotic factors chosen for soil conditioning can impact the revegetation processes (Kuťáková et al., 2020). Considering the pollinator network, active restoration with planting and the addition of topsoil appears to accelerate the recovery of ecological processes, achieving similar functionality to natural ecosystems, thanks to the improvement of practices that consider wild bee communities and ameliorate flower resource availability (Carvalho et al., 2022). Gentili et al. (2020) found that the chemical and physical properties of the backfilling materials used for slope reclamation had a more significant impact on the return of natural conditions to quarry slopes. In summary, the efficacy of active restoration methods is highly variable, with outcomes being contingent upon the specific bioindicator monitored, the type of intervention applied, and the temporal scale of the assessment.

Finally, active restoration can include simple sowing or planting. For example, 10 studies investigated the best way to recover quarries without any soil amendment or improvement. Seven have assessed which mix of seeds and plant species is most effective for recovery, agreeing on the use of native and pioneer species (Ruthrof et al., 2009; Łuczak et al., 2019; Luo et al., 2021). A study on Carabids showed a higher colonization rate in quarries restored with sowing and planting projects (Hula & Šťastná, 2010a). These plant species possess characteristics that allow them to survive in degraded environments, with a scarce presence of organic and nutritious matter in the soil. This underscores the importance of tailoring rehabilitation strategies to the specific ecological and environmental context of each quarry site, considering factors such as soil composition, climate, and local flora and fauna (Werner et al., 2001; Łuczak et al., 2019; Luo et al., 2021). These have analyzed mostly plants as "agents" of restoration dynamics and processes. Indeed, Raizada and Juyal (2012) examined the effects of the introduction of fast-growing leguminous species and bioengineering on the variety of trees, the secondary succession, and the productivity of *Acacia catechu* seeds. The results show that fast-growing leguminous species reduced diversity and hindered the regeneration and growth of native vegetation (Jha et al., 1995; Abraham et al., 2009). Gilardelli, Sgorbati, Citterio, & Gentili (2016) examined the potential of three herbaceous species, common in calcareous grasslands, to contribute to the stability of the top layers of dump deposits, demonstrating that although hayseed was the most costly and time-consuming method, it resulted in greater species diversity, better vegetation structure, and more greening. However, the use of fruit tree and shrub plantings can also reduce reclamation costs and enhance the ecological potential of new biotopes under anthropogenic pressure, even if they are not strictly typical of calcareous biocenosis (Łuczak et al., 2019). Nevertheless, these results emphasize that using native plants and seed mixes, although with slow growth, can enhance the restoration of excavation areas by preventing the spread of non-native species and boosting natural regeneration and biodiversity (Oliveira et al., 2014).

Artificial revegetation promotes quicker species establishment, reduces visual impact, minimizes soil erosion and runoff, and creates favorable microclimatic conditions for colonization by other species (Werner et al., 2001). This highlights the diverse approaches and methodologies employed in the field of quarry restoration, underscoring its complexity and multidisciplinary character.

The studies reviewed do not directly link restoration outcomes to no-net-loss or biodiversity offset goals. Quarry restoration, by mitigating habitat destruction, can help compensate for biodiversity losses and support regional or national no-net-loss targets, though achieving this remains challenging (Gardner et al., 2013; Souza & Sánchez, 2018).

Moreover, most studies on quarry restoration only considered species lists or community composition itself, failing to apply a trait-based approach central to theoretical frameworks for achieving functional restoration targets and to better understand the community and ecosystem services response to environmental conditions dictated by restoration processes (Díaz et al., 2007; Laughlin, 2014). Once again, these results show that the choice of recovery method must be decided considering different ecological, functional, and ecosystem functionality aspects so as not to limit biodiversity levels. One potential approach could involve creating a mosaic of habitats with varying vegetation cover and soil structures to fulfill the needs of different species' ecology. Monitoring and adjusting recovery practices based on species' responses will be essential to ensure that rehabilitation efforts are beneficial for a broader range of vegetation and fauna.

Spontaneous Restoration. Unlike technical reclamation, this method relies on natural processes to restore the quarry sites, with no direct sowing or planting involved. Instead, the focus is on allowing native plants to colonize the area naturally. However, some management could be necessary to suppress invasive plant species or mitigate too harsh environmental conditions that could disrupt the natural succession process (Stephan & Hubbart, 2022). This approach encourages the development of a diverse and resilient ecosystem over time, as plants and animals gradually may return to the area. However, it is necessary to specify that this is a very slow process, which could take even hundreds of years to achieve good results (Mexia et al., 2020).

Almost 20% of the total restoration studies have analyzed spontaneously restored quarries ($N = 14$). Generally, limestone quarries can lead to naturally recruited herbaceous vegetation that resembles mesophilous grassland, despite initial substrate conditions being more similar to rupicolous or xerophilous grasslands (Pitz et al., 2018), or woodland after approximately 20 years (Prach et al., 2014). Limestone quarries are more comparable, among each other, in species composition during the initial and early stages of succession, dominated by synanthropic and r-strategy species, mostly because of poor soil conditions (Khater et al., 2003; Prach et al., 2014). Native perennial species colonize quarry embankments significantly after a decrease in annual plant species, with their colonization capacity mainly restricted to clonal spreading or long-term establishment (Khater et al., 2003). Moreover, considering functional and ecological traits, it has been observed that community specialization generally increased during succession due to a decline in generalists and an increase in grassland specialists and threatened species (Ballesteros et al., 2023).

The factors that directly contribute to the restoration trajectory are manifold. Indeed, this process is influenced by both abiotic and biotic factors. It has been found that vegetation establishment in the pioneer phase is affected mainly by abiotic filters, such as soil organic matter, moisture, and bulk density, leading to the dominance of ruderal and annual/alien species (Gilardelli, Sgorbati, Armiraglio, et al., 2016). This is because the soil is extremely hard, compacted and nutrient-poor, facilitating mainly gramineous and drought-tolerant plant species (Duan et al., 2008). Shrubland communities progressively replaced pioneer communities over approximately 22–41 years, suggesting that certain successional phases should be a shortcut to direct spontaneous succession toward target habitats (Gilardelli, Sgorbati, Citterio, & Gentili, 2016). Thus, biotic filters, such as inter-species competition, become more important as succession proceeds, because the physical environment becomes more favorable (i.e. due to organic matter accumulation), allowing a greater variety of species to colonize this environment (Duan et al., 2008; Stephan & Hubbart, 2022). Moreover, it is important to also consider the vegetation community in the proximity of the quarry. In fact, it can influence the re-vegetation process and its structure (Prach et al., 2015), but it has a minimal impact on the microbial communities, which are more affected by local plant species and soil chemical conditions (Mészárošová et al. 2024).

Therefore, these differences in successional trajectories suggest that conservation management should adopt a site-specific approach, with the highest success probabilities on limestone being restored to calcareous grassland analogues (Bashirzadeh et al., 2022). Benefits of natural rehabilitation include recruitment of uncommon native biodiversity, reduced initial cost, and reduced long-term maintenance cost (Prach et al., 2014; Bashirzadeh et al., 2022). Also, assessing spatiotemporal changes in community specialization helps evaluate and track successional trends and determine the conservation and restoration status of degraded areas (Ballesteros et al., 2023). Restoration measures of surrounding areas should be considered if ownership and legislation allow them (Prach & Tolvanen, 2016), and suitable species for restoration should be able to disperse, produce viable seeds, be competitive under local conditions and be perennial (Khater et al., 2003; Duan et al., 2008). Thus, some authors suggest that, although more expensive in terms of labor and money, technical restoration can be used to speed up the process and ensure successful vegetative succession, using native and stress-tolerant plant species and monitoring exotic species (Duan et al., 2008; Gilardelli, Sgorbati, Armiraglio, et al., 2016; Bashirzadeh et al., 2022).

This main focus on restoration processes allows for a broader understanding of the dynamics behind the restoration processes after quarry abandonment and the best method to recover these post-industrial sites (Neri & Sánchez, 2010). However, it must be highlighted that a noticeable knowledge gap exists, because the research focused on active sites constitutes a minority of the total studies. This underrepresentation of active sites suggests a potential shortfall in our understanding of the immediate ecological impacts of ongoing extraction activities, as well as in their neighborhoods. Given the heterogeneous nature of active sites and the immediate environmental impacts, this knowledge gap could have significant consequences for effective management and mitigation strategies (Lee et al., 2024).

Our analysis also highlights the significant field constraints and limitations during limestone quarry restoration. The calcareous substrate conditions, characterized by a general lack of nutrients and harsh climatic conditions, represent a major challenge for plant establishment and growth and the subsequent faunal colonization. However, these can create a unique environment for both endangered and specialized species, highlighting the importance of maintaining early successional sites. Given the limited spontaneous recolonization from surrounding areas, the introduction of a diverse mix of native species, guided by a trait-based approach, can be useful for accelerating biodiversity recovery. Also, it would be necessary to suppress invasive species, during the early successional stages. These actions, when combined with long-term monitoring, can help to guide the restoration trajectory towards a more resilient and biodiverse ecosystem.

Conclusion

Cement is one of the most important materials for the economic and social development of humanity. Limestone quarries are key areas for its production. As we have demonstrated, these anthropized habitats harbor a rich biodiversity, characterized by organisms specialized in nutrient-poor and harsh environmental conditions, ranging from bacteria and fungi to plants and animals. Nonetheless, these habitats harbor assemblages that differ from those of intact natural ecosystems, which underscores the importance of quarries as complementary rather than substitutive habitats.

The impacts of quarrying activity on these communities are still overlooked. We have underlined the diverse approaches and methodologies employed in the field of quarry restoration, which can be achieved both naturally and artificially. However, we have highlighted that even with natural restoration, which is better in monetary and management terms, some active management actions are still required to achieve restoration success. Currently, most studies focus on plants, while there is a considerable gap in the understanding of vertebrate and invertebrate biodiversity within these sites. Studies mainly focused on abandoned or restored sites, looking at how plants change and how to best restore them. From a methodological point of view, it is imperative to incorporate control areas and additional extractive sites (when studying a single site), assess the presence of species with conservation value, and the study of a broader range of bioindicators. Such measures will provide a more comprehensive understanding of biodiversity in these unique environments, ultimately contributing to more effective conservation and management strategies, providing a balance between biodiversity conservation and increasing cement demand. In conclusion, by synthesizing a broader and more geographically diverse set of studies and incorporating functional trait perspectives, this review not only updates but also substantially extends previous studies (Tropek et al., 2010; Prach & Tolvanen, 2016). The findings herein provide a solid foundation for future research and practice, emphasizing the importance of a holistic approach to biodiversity recovery in these human-modified landscapes.

Acknowledgments

We sincerely thank Dr. Martina Nasuelli for her valuable assistance in writing this review. Open access publishing facilitated by Universita degli Studi del Piemonte Orientale Amedeo Avogadro, as part of the Wiley - CRUI-CARE agreement.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Dataset of reviewed studies on limestone quarry restoration, with all information provided in the review.
Table S2. Dataset of reviewed studies on limestone quarry biodiversity assessment, with all information provided in the review.
Table S3. Dataset of reviewed studies on limestone quarry impacts, with all information provided in the review.
Table S4. Dataset of studies included in this review but not pertinent in the discussion section.
Table S5. Dataset of scientific journals where all reviewed studies were published.

Coordinating Editor: Subodh Kumar Maiti

Received: 24 June, 2025; First decision: 16 September, 2025; Revised: 31 October, 2025; Accepted: 31 October, 2025