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Plant Community, Soil and Microclimate Attributes after 70 Years of Natural Recovery of an Abandoned Limestone Quarry

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Abstract: With globally more than 100,000 km^2 impacted by surface mining at present, and with increasing demand for surface-mined products, land managers are challenged to address landscape degradation of decommissioned quarries, especially in urban areas. In this study, soil, microclimate, and vegetation community data were collected from geomorphologically distinct locations (quarry floor, platform with pond, quarry top, highwall edge) within an urban limestone quarry abandoned 70 years ago without reclamation in central Missouri, USA. Results were compared with two nearby reference sites to bookend conditions in the abandoned quarry, including a recently closed quarry and an urban forest. Results of this study showed that abiotic mining legacies gave rise to distinct vegetation communities comprising 74 native species but also 21 non-native species. Species richness was increased near persistent edges (cliff edge, pond edge) and approached the lower range of species richness found in natural areas in the region. The results of this case study are congruent with the growing body of studies about spontaneous succession on abandoned surface mines worldwide in that spontaneous (vs. managed) revegetation can lead to species-rich, near-natural communities. This finding may justify revision of current legislation requiring technical reclamation of surface mines, especially where favorable substrate, such as limestone, is conducive to swift onset of revegetation. To improve the ecological value of such areas, the provision of funding for long-term invasive species management should also be considered.

Keywords: surface mine; urban quarry restoration; non-technical reclamation; natural succession; species diversity; floristic quality; invasive species; micro-climate; quarry soil

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1. Introduction

Landscape degradation is one of the most detrimental, immediate outcomes of surface mining for limestone, an important raw material widely used for agriculture, industry, and architecture [1]. Economic development and the growth of urban areas in many countries have increased the need for limestone [2,3], which in turn, has resulted in the creation of a large number of quarry sites [4]. Limestone demand is predicted to continue to increase in the future [5], and with it landscape degradation as, eventually following resource extraction, surface mines cease operations and under-burden geologic landforms remain exposed [6,7]. While many countries have implemented policies requiring mining companies to carry out post-mining land restoration [8,9], prior to the creation of such policies, limestone quarries were abandoned without having been restored. Some abandoned quarries have since become enveloped by urban expansion [10]. These quarries present distinct challenges to urban managers such as foresters, and parks and recreation engineers charged with addressing what are often significant negative visual impacts and the erosion potential that represents risks to human safety [11].

Post-mining landscapes are characterized by poor soil structure, water and nutrient deficiencies, and coarse residual substrate. These immediate adverse conditions coupled with critical distance from natural areas, i.e., limited propagules, represent obstacles to swift spontaneous succession [12–17]. Prior to around the year 2000, scientific investigations of spontaneous recovery were uncommon [18–20], and most studies of quarry reclamation focused on the techniques that alter the post-mining surface to support (any) vegetation [21,22], or to introduce species that can survive on harsh substrates [9,23,24]. Technical options for reclamation vary in cost but are generally quite expensive [25]. Some reclamation methods include backfilling exposed quarry walls or portions of a quarry with removed overburden material, adding organic matter or nutrients to improve soil quality, or reestablishing vegetation through planting, sowing or hydroseeding [17,22,26–29]. In urban settings, under pressure from the public, managers may aim to quickly improve aesthetics and mitigate short-term erosion of recent quarries via the "immediate green effect" [30,31]. However, if this is achieved through the establishment of a few competitive grass species available in commercial seed mixes, these grass species tend to preclude other species from establishing and, thus, can obstruct or divert the trajectory of long-term succession, ultimately resulting in an undesirable vegetated state [16]. Similarly, reclaiming quarries through the planting of woody vegetation can competitively exclude herbaceous species, potentially decreasing overall diversity [25].

In contrast, minimal intervention via providing native propagules from similar habitats [16,32,33], or allowing completely spontaneous (natural) vegetation reestablishment often results in a plant community more closely mimicking the former natural community, with higher diversity than achieved through managed, non-native seeding [20,31]. Natural succession can result in continuous vegetation cover dominated by native species within 15 years, especially when the site is small, surrounded by natural vegetation, and lacks extreme moisture, pH, and nutrient conditions [34]. Species richness in these initially herbaceous plant communities may remain high for decades until woody vegetation matures [35]. In addition, in regions of intense industry or agriculture, some abandoned quarries serve as refugia for rare or endemic organisms, such as lichens and bryophytes, vascular plants, birds and insects [7,12,36–39].

The potential for the establishment of diverse plant communities in abandoned limestone quarries is, in addition to the initial absence of trees, related to topographic complexity involving vertical features (high walls or cliffs), platforms (elevated or below grade with the potential for ponding), and spoil heaps. The array of unique microclimatic and soil conditions in these sites may lead to distinctive plant assemblages that retain distinctness in the long term due to the persistence of these topographic features. In the state of Missouri, USA, the Land Reclamation Act [40], passed in 1990, requires all industrial mineral surface mining operations, including limestone, to uphold a strict plan of reclamation. However, many Missouri quarries were abandoned prior to the 1990 legislative action. Since they were not reclaimed and left to naturally regenerate, they now provide the opportunity to assess long-term outcomes of spontaneous succession in an array of microsites differing in abiotic conditions. The objectives of the current work were to quantify (a) the heterogeneity in and (b) relationships between soil physical and chemical parameters, microclimate, and vegetation composition in a Missouri limestone quarry 70 years after its abandonment. The goal was to provide quantitative science-based information to improve management of abandoned quarries.

2. Materials and Methods

2.1. Study Site

This study was conducted within city limits of Jefferson City (38°33′30.63″ N, 92°10′23.97″ W) in central Missouri, USA. Jefferson City has a humid continental climate with hot, rainy summers and cold winters. Average annual precipitation is 1100 mm and annual mean daily temperature is 12.9 °C (−0.9 °C in January, 25.7 °C in July) [41]. Study site elevations ranged from 190 to 235 m a.s.l. Soils, derived from dolomitic bedrock, are shallow to deep, moderately to well drained mesic oxaquic hapludalfs and lithic hapludolls in the Gatewood-Moko Complex and Wengart soil series [42]. Native upland vegetation of the region comprises oak-hickory forest [43]. Commonly encountered species at the study sites included *Quercus stellata* Wangenh. (post oak), *Carya ovata* (Mill.) K. Koch (shagbark hickory), *Juniperus virginiana* L. (eastern redcedar), *Fraxinus americana* L. (white ash), and *Ulmus americana* L. (American elm).

The primary study site (Q70) is a magnesium limestone (Jefferson City dolomite; $CaMg(CO_3)_2$) quarry abandoned in the early 1940s, i.e., about 70 years prior to this study. This fenced, 2-ha area is part of the campus of Lincoln University since the early 1990s. This quarry is 20 m deep with one platform about halfway between the quarry floor and the quarry top (Figure 1a). Two reference sites included an urban forest (UF) and a dolomite quarry (Q1) in which operations ceased one year prior to the begin of this study (Figure 1). UF is about 500 m from Q70; it is also owned by Lincoln University but open to the public. UF was never quarried and not disturbed for the last 100 years prior to the study. Q1 is owned by Capital Quarries Inc. and located along Highway 54 S, about 3.5 km from Q70. This quarry is located on a former hillslope, with 30 m vertical walls at the deepest point; limestone material is extracted through blasting and, subsequently, crushed to different aggregate sizes for use in construction or milled for use in agriculture (Ag lime). The two reference sites were selected to bookend conditions of soil development, microclimate and natural vegetation succession in the abandoned quarry.

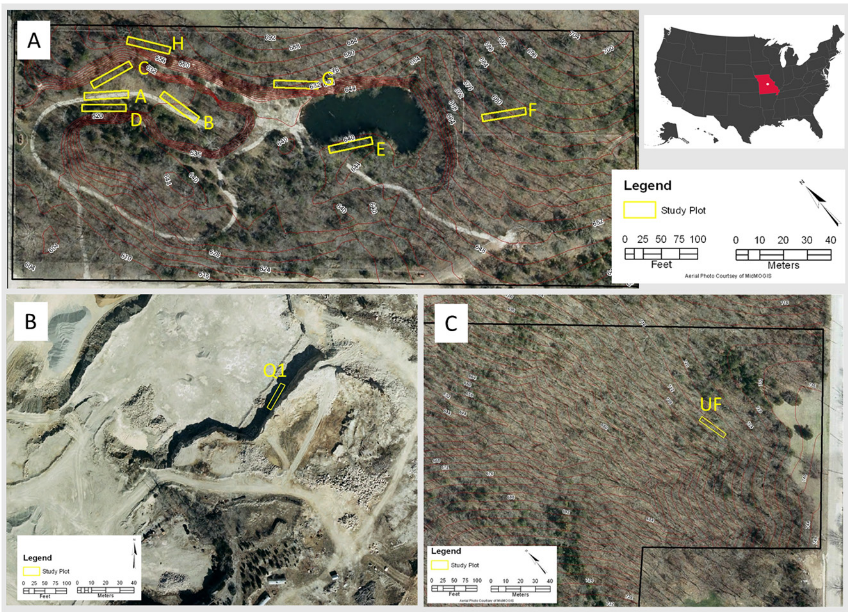

Figure 1. Locations of 20-m × 3-m study plots in (**A**) a quarry abandoned 70 years prior to the study (site Q70; with eight study plots labeled A–H), (**B**) a reference quarry that ceased operations 1 year prior to the study (site Q1 with the study plot also labeled Q1), and (**C**) an urban forest reference site that was never quarried and with trees over 100 years old (site UF with the study plot also labeled UF). The solid black lines represent property boundaries that are fenced (**A**) or unfenced (**C**). All study sites are within city limits of Jefferson City, Missouri, USA (inset map).

2.2. Data Collection

To sample soil, microclimate, and vegetation characteristics, 20-m × 3-m plots were established at each site. At Q70 (Figures 1a and 2a), eight plots were set up on level ground of geomorphologically distinct features on the quarry floor and quarry top. On the quarry floor, a total of five plots were placed on an overgrown gravel road (plot A), a wet area below a platform with pond (plot B), near a south and north-facing highwall (plot C and D), and near the pond's edge on a below-grade platform (plot E). At the quarry top, a total of three plots were placed near the cliff edge (plots G and H) and approximately 20 m from the cliff edge (plot F) (Figure 1a). At each reference site, one plot was established (Figures 1b,c and 2b,c) as the vegetation was relatively homogenous and due to limited funding.

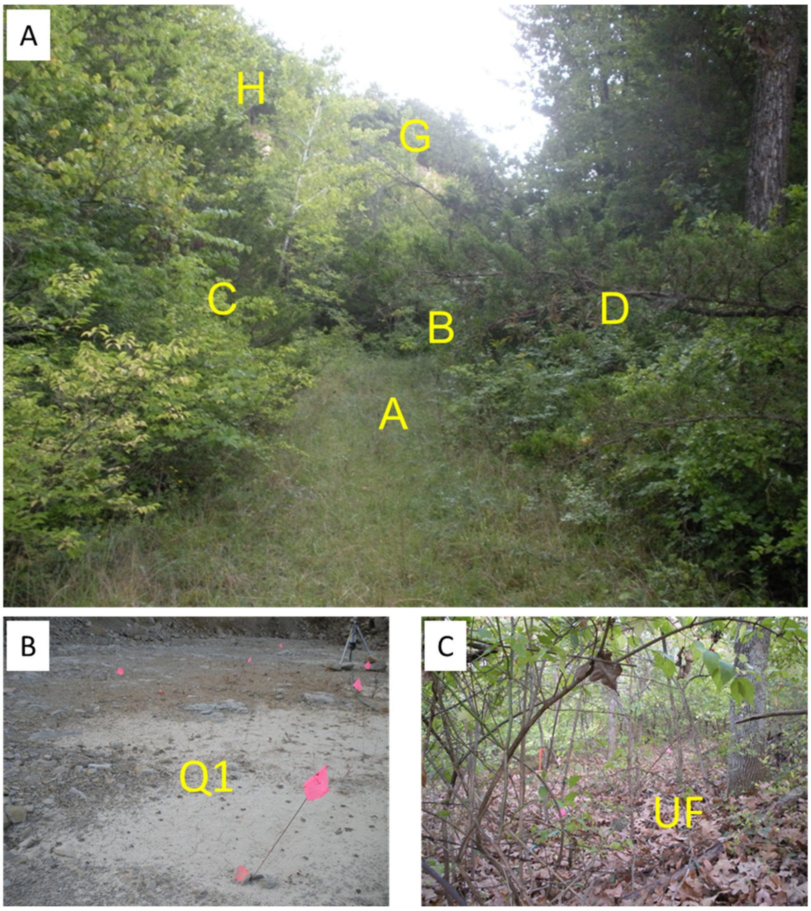

Figure 2. Photographs of study plots in (**A**) a quarry abandoned 70 years prior to the study (Q70), (**B**) a reference quarry that ceased operations 1 year prior to the study (Q1), and (**C**) an urban forest reference site that was never quarried and with trees over 100 years old (UF). Letters indicate approximate locations of study plots in Q70; plots A–D are on the quarry floor (Plot E is not visible), plots G and H are on the quarry top (Plot F is not visible). Plots Q1 and UF are in sites with the same respective names. Photos are directed south, north, and south for the three sites, respectively. The climate station is seen in Q1; pink flags indicate locations of sampling quadrats. All study sites are within city limits of Jefferson City, MO, USA.

Vegetation characteristics were determined in 20 square 1-m^2 subplots (sampling quadrats) in each study plot in late summer 2010. Subplots were established along two parallel transects spanning the length of each plot. Ten subplots were spaced equally along the two transects, so that the subplots were spaced 1 m apart along and between transects. A 1-m^2 sampling frame was placed on the ground to delineate the subplot. Each understory species rooted within a sampling quadrat was identified to species level if possible, and its foliar cover (as area projected onto the ground) was estimated to the nearest 1 cm^2. Cover was recorded separately for herbaceous plants $\leq$1 m in height, and for woody plants $\leq$2 m in height. Data were averaged across the 20 subplots per plot and expressed in percent (i.e., m^2 projected plant cover per m^2 of ground area $\times$ 100).

Several floristic quality indicators were determined for each plot: species richness, diversity, percentage of non-native species, and coefficient of conservatism. Species richness (S) is the total number of species present in the 20 m^2 sampled per plot. Diversity was quantified using the Shannon-Wiener Diversity (H), an index that accounts for both the number of species present and how equitable the species' contributions to the community are (i.e., evenness) [44]. H increases with increasing species richness and with increasingly equitable contributions of each species to the community. The Shannon-Wiener Diversity Index is calculated as

$$H = -\sum_{i=1}^{s} Pi \ln Pi \quad (1)$$

where Pi is the relative abundance of each herbaceous species in the plot and where s is the number of species [44]. Each native Missouri species was assigned a coefficient of conservatism (C) [45,46] following the methodology and philosophy detailed in [47] and [48]. Coefficients of conservatism range from 0 to 10 and represent an estimated probability that a plant is likely to occur in a landscape relatively unaltered from what is believed to be pre-European settlement condition. A C of 0, therefore, is assigned to plants that have demonstrated little fidelity to any remnant natural community, i.e., may be found almost anywhere, while a C of 10 is applied to those plants that are almost always restricted to a pre-settlement remnant, i.e., a high-quality natural area. Non-native species are assigned a 0 by default. Plot-level C was calculated by summing all individual species' abundance-weighted C.

Overstory (tree) characteristics were sampled using the entire 20-m^2 plot. Tree species were identified, and tree diameters were measured at breast height (DBH) for trees $\geq$12 cm DBH, or at the stem base for trees <12 cm DBH but $\geq$2.5 cm basal diameter. Tree age for the three trees with the largest diameters in or near each plot was determined by counting tree rings from cores extracted at breast height (1.37 m).

Soil physical and chemical properties were determined using soil sub-samples from two soil cores (5 cm diameter) per vegetation sampling quadrat, collected from the top 5 cm of mineral soil (i.e., 40 cores per plot) in September 2010. One core per quadrat was used to determine bulk density (after drying at 105 °C for 48 h) and particle size distribution between gravel (>2 mm), sand (2 mm–0.052 mm) and silt/clay (<0.052 mm) using a sieve shaker run for 10 min. The second core was air-dried, sieved (2 mm mesh), and used to determine chemical properties. Values of pH were determined from 1 g of soil <2 mm in 20 mL DI water [49]. Phosphate and various cations (K, Ca, Mg, Mn, Na, B, Cu, Zn, Al, and Fe) were extracted using the Mehlich III procedure using 3 g of dry soil in 30 mL extracting solution [50]. Phosphate concentrations were determined photometrically; concentrations of each cation were determined using inductively coupled plasma optical emission spectrometry (ICP-OES; Agilent Technologies, Santa Clara, CA, USA) [50].

Microclimate was recorded in each of the ten plots during the 2011 water year (1 October 2010 to 30 September 2011). Microclimate stations with instruments supplied by METER Group, Inc., (Pullman, WA, USA) were installed in September 2010. Data were recorded hourly (Em50 data logger) for air temperature and relative humidity 1 m above the ground (RH/Temp sensor with radiation shield), solar radiation at 1.1 m above ground (PYR total solar radiation sensor), and soil moisture, temperature and electrical conductivity 5 cm below ground (5TE soil sensor). Soil moisture, temperature, and electrical conductivity were collected in triplicate at each site using three probes installed approximately 1–2 m apart per plot; measurements of the three probes were averaged prior to analyses. Time-series data were post-processed for missing and incorrect data (due to sensor malfunction). Gaps were corrected using interpolation.

2.3. Data Analysis

Descriptive statistics were calculated for soil, microclimate, and plant variables for each site of this case study. Multivariate Statistics in Canoco 5 [51] were employed to identify relationships between these abiotic and biotic plot characteristics. To display differences between plots based on the plant community composition, unconstrained analyses (Detrended Correspondence Analysis, DCA) were conducted. To quantitatively characterize how abiotic site characteristics (e.g., physical soil characteristics, soil chemical composition, microclimate) were contributing to the observed differences in species composition between plots, constrained analyses (Canonical Correspondence Analysis, CCA) were conducted [52,53]. In these analyses, plant species cover data were log transformed and rare species downweighted.

The CCA, using soil characteristics as environmental predictors, was conducted at the quadrat level (*n* = 200 quadrats); this would not have been possible at the plot level with the number of explanatory variables (soil physical: four, soil chemical: 12) exceeding the number of plots (*n* = 10). Initially, highly autocorrelated environmental variables were eliminated; i.e., of the three particle size distribution variables gravel, sand, silt/clay, only gravel was retained. All variables retained had a Variance Inflation Factor (VIF) less than 6. Then, statistically significant ($p \leq 0.05$) explanatory variables were selected via forward selection; in this process, Zn and Na were found to be not significant and were eliminated from the analysis.

Microclimate characteristics were available at the plot level only. Since the number of predictors (six) was large compared to the number of plots (*n* = 10), the CCA could be conducted with only three of the six microclimate variables as explanatory variables, to not render the constrained ordination model, in effect, unconstrained and permutation tests unreliable [51]. Microclimate variables used in the analysis represented the mean of daily means of the growing season (1 May–30 September, 2011).

3. Results

In the current study, soil physical and chemical characteristics, microclimate, and vegetation composition showed appreciable variability among the plots in the 70-year-old abandoned quarry (Q70) and between Q70 and the two reference sites (Figure 3, Tables S1–S3 in Supplementary Materials). As might be expected, differences were apparent between Q70 quarry floor and the non-quarried surface of the quarry top. For several characteristics (detailed below), the quarry floor was similar to the recently decommissioned quarry (Q1), and the Q70 quarry top was similar to the urban forest (UF).

3.1. Soil

In the comparison of soil characteristics, Q70 quarry floor soil still clearly resembled Q1 with gravel content exceeding 60%; whereas sand was the dominant particle size at Q70 quarry top and UF (Figure 3a). The difference between Q70 quarry floor and top were less pronounced with respect to bulk density, reflecting 70 years of soil formation processes (weathering and organic matter accumulation) at Q70 quarry floor. As a result, Q70 quarry flow had distinctly lesser bulk density in comparison to Q1 (Figure 3b). Bulk density at Q70 quarry floor was highest in Plot A; this was presumably attributable to plot A being located on an overgrown path that had been amended with gravel in the past. Soil sampling at Q1 was biased towards sampling areas where bedrock had weathered sufficiently to take a sample (due to limitations of the sampling equipment), explaining measured bulk densities below those of the dolomite bedrock (2.84 g cm^{-3}). Mg (Figure 3c) and Ca concentrations were about two times greater at Q1 and Q70 quarry floor than at Q70 quarry top and UF; this likely resulted from the high proportion of gravel, the weatherable source material ($CaMg(CO_3)_2$) for these elements, in these plots. In fact, gravel content was found to be highly correlated with soil Mg concentrations (R^2 = 0.77). Mg also correlated with pH (R^2 = 0.81) which was expectedly highest in Q1 (8.8), and higher at the Q70 quarry floor (7.8) than quarry top (6.7). Plots with presumably the deepest, least disturbed soils at UF and Q70 quarry top Plot F (located at a distance from the cliff edge), had the lowest, slightly acidic pH of about 6.3 (Figure 3d). Micronutrients Fe and Mn also differed between plots. Fe concentrations were low in Q1, highest in UF, and intermediate in Q70 (Figure 3e). Mn concentrations were lower in Q1 and at Q70 quarry floor than at Q70 quarry top and UF (Figure 3f); Mn correlated negatively with pH ($R^2 = -0.52$). Al concentrations (Table S1) also negatively correlated with pH ($R_2 = -0.67$), with higher Al concentrations occurring at Q70 quarry top and UF. Of the additional elements extracted (P, B, Cu, K, Na, Zn), concentrations of P, K, Cu and Zn were generally lowest at Q1 and higher in all other plots (Table S1), but an obvious pattern between Q1, Q70 quarry floor and top and UF was not detected. There was no difference in B and Na concentrations between the plots (Table S1).

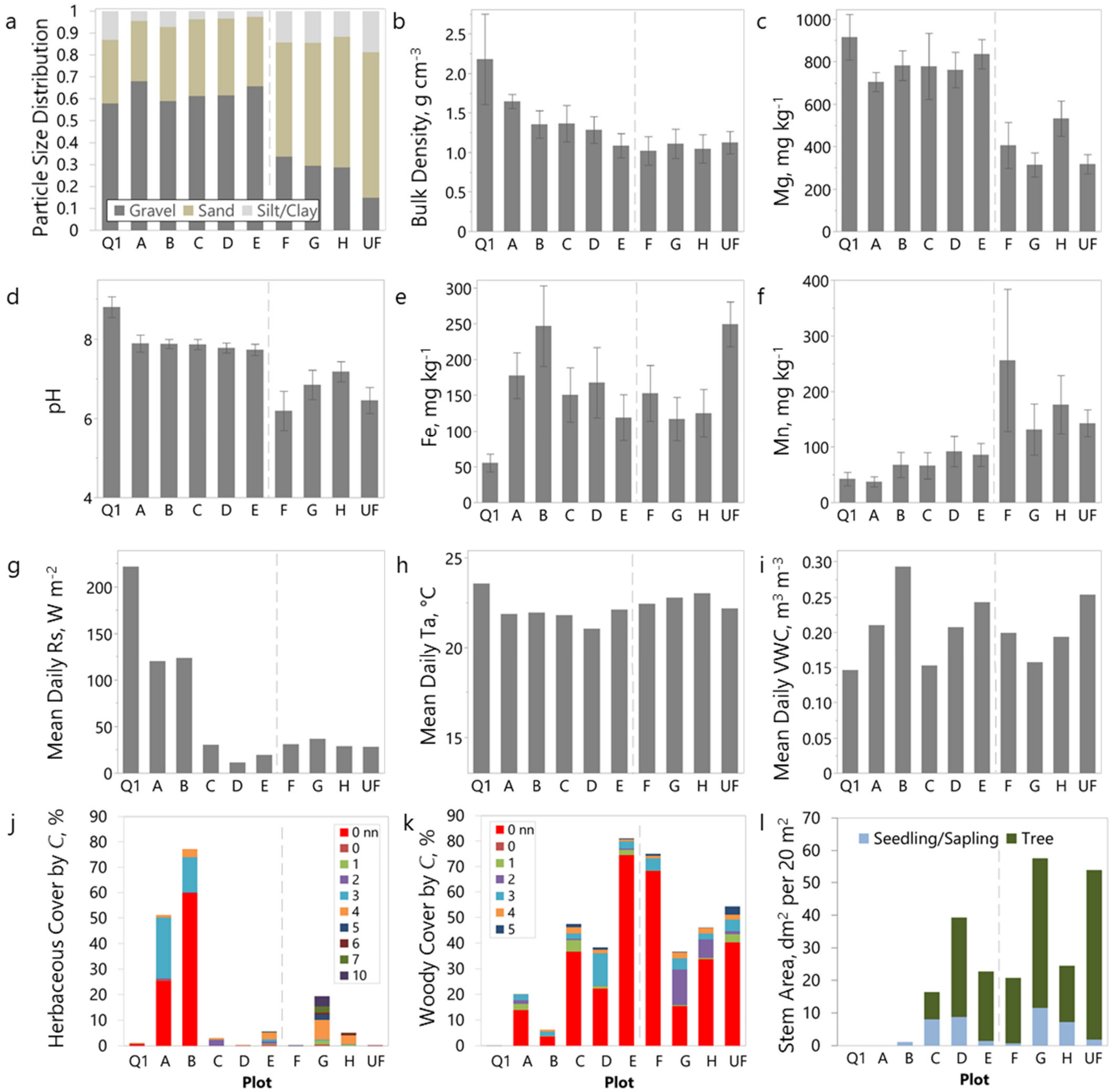

Figure 3. Select soil physical (**a**,**b**) and chemical (**c**–**f**) characteristics, microclimate (**g**–**i**), and vegetation composition characteristics (**j**–**l**) in eight plots of a 70-year-old abandoned quarry (Plots A–E: quarry floor, F–H: quarry top), a recently decommissioned reference quarry (Q1), and an urban forest reference site (UF) in Jefferson City, Missouri, USA. The vertical dashed line separates quarried surface (left) and non-quarried surface (right). Error bars, if shown, represent 1 SD (n = 20 quadrats). Microclimate data (**g**–**i**) are shown for the growing season (1 May–30 September); error bars are omitted as they would show temporal variation that was almost identical between sites. Rs—shortwave radiation, Ta—air temperature, VWC—volumetric water content. C is the Coefficient of Conservatism; 0 nn is C = 0 for non-native species. Woody cover (**k**) is from plants 0–2 m high.

3.2. Microclimate and Vegetation

Microclimate varied between plots, but, in contrast to soil characteristics, differences were driven by factors other than the distinction between quarried surface versus non-quarried surface. Mean daily shortwave solar radiation (Rs) differed between plots by two orders of magnitude. Rs was expectedly highest in plots without tree canopy or topographic shading (plots Q1, A, B in Figure 3g, Table S2). Rs was lowest in plots D and E which have topographic shading from quarry walls on their south sides and a tree canopy (Figure 3l). Radiation differences resulted in a similar pattern of daily mean air temperature (Ta) (Figure 3h, Table S2) reached in the study plots with mean Ta of the warmest plot (Q1) being 2.5 °C greater than that of the coolest plot (D). Mean daily VWC in the driest plots (0.15) was about half to two-thirds that of the wettest plots (0.25–0.3) (Figure 3i, Table S2). VWC was lowest at the recently decommissioned quarry Q1 and plots C and G at Q70, with several factors explaining this. At the time of this investigation, there was a lack of soil and shading at Q1, and at G the southerly exposure at the cliff edge likely enabled high evaporation from the soil and transpiration by trees (Figure 3l); a combination of these factors may explain the relatively low VWC at plot C, located at the base of a south-facing cliff wall. Highest VWC was measured in Q70 plot B located below a platform holding the quarry pond, plot E located in a riparian area, and UF which was on a slope with NE aspect (Figure 3i). RH, Ts, EC (Table S2) also varied between plots; they were highly correlated with Ta and VWC (see multivariate analyses results below) and, thus, not discussed independently.

A total of 94 understory species were recorded across the entire study area (Table S3) with highest S (38 in Plot E) occurring in plots of the abandoned quarry and lowest S (15, 22) occurring at the reference sites Q1 and UF, respectively (Table 1). Herbaceous cover was highest at Q70 quarry floor (site A 51%, site B 77%); in these sites, the cover of woody understory was low (20% and 6%, respectively) (Table 1) and a canopy of large trees was absent (Figure 3l). Understory cover in the Urban Forest plot was dominated by woody plants (54%) with very little herbaceous cover (0.2%). As anticipated, understory cover in the recently decommissioned quarry was very low (1.2%) (Table 1). In all plots, non-native species were present. The proportion of total cover made up by non-native plants ranged from 0% (Plots D, F-H) to 77% (Plot B) for herbaceous plants; high values were mostly due to tall fescue (*Festuca arundinacea* Schreb.) (Table 1 and Table S3, Figure 3j). Excluding Q1 in which no woody plants were present, relative cover of non-native woody plants ranged from 42% (Plot G at quarry top) to 92% (riparian Plot E at quarry floor), mostly due to honeysuckle species (*Lonicera japonica* Thunb., *L. maackii* (Rupr.) Herder, *L. x bella*). The Urban Forest plot had a moderate to high contribution to total cover by non-native plants: 9% and 74% for herbaceous and woody plants, respectively (Table 1, Figure 3k).

Table 1. Vegetation characteristics in eight plots of a 70-year-old abandoned quarry (Plots A–E: quarry floor, F–H: quarry top), one plot of a recently decommissioned reference quarry (Q1), and in one plot in an urban forest reference site (UF). Study sites are located in Jefferson City, MO, USA. Herbaceous (Herb.) vegetation was recorded at ≤1 m height; woody (Wd.) vegetation was recorded at 0–2 m height. S—species richness, H—Shannon-Wiener Diversity index, J—Pielou's evenness, and *C*—Coefficient of Conservatism are based on the 20-m^2 of sampled plot area.

Plot	Cover (dm^2 m^{-2}, %)			S			H			C			% Exotic Species		% Exotic Cover		Tree Age
	Herb.	Wd.	Total	Herb.	Wd.	Total	Herb.	Wd.	Total	Herb.	Wd.	Total	Herb.	Wd.	Herb.	Wd.	(y, SD)
Q1	1.1	0.03	1.1	13	2	15	2.1	0.2	2.2	1.1	2	1.1	54	0	42	0	n/a
A	51.2	20.1	71.4	21	11	32	1.3	1.2	1.9	1.5	0.6	1.2	33	36	50	69	n/a
B	77.2	6.3	83.5	19	7	26	0.8	1.2	1.1	0.7	1.4	0.8	37	43	77	56	n/a
C	3	47.4	50.4	9	20	29	1.3	1.5	1.7	2.4	0.6	0.7	22	30	1	77	28 (10)
D	0.3	38.3	38.6	5	18	23	1	2	2	3.3	1.3	1.3	20	33	0	58	42 (19)
E	5.5	81.1	86.6	16	22	38	2.2	1.5	1.8	3.1	0.2	0.4	31	32	2	92	46 (10)
F	0.2	75	75.2	1	12	13	0	0.4	0.4	10	0.3	0.3	0	33	0	91	63 (19)
G	19.4	36.6	56	17	13	30	2.2	1.8	2.6	5.5	1.4	2.8	0	38	0	42	85 (4)
H	5.1	46.1	51.2	10	19	29	1.8	1.6	2	4.2	0.7	1	0	26	0	73	57 (5)
UF	0.2	54.3	54.5	4	18	22	0.9	1.7	1.7	3.2	0.8	0.8	25	22	9	74	70 (29)

The Coefficient of Conservatism of species encountered at the study sites ranged from 1–10 for herbaceous species (mean $C = 4$) and 1–5 for woody species (mean $C = 3$); among those were nine high-quality (i.e., $C \geq 5$) herbaceous species (including an orchid) and five woody species (Table S3). However, the high incidence of non-native plants was reflected in generally low plot-level values for the Coefficient of Conservatism, especially for woody understory (Table 1). Plot G, at the quarry top cliff edge of Q70 had the highest, yet moderate floristic plot-level quality with $C = 5.5$ for the herbaceous plant community. While a plot-level C of 10 was calculated for the herbaceous community of plot F of Q70, this was due to the sporadic presence (2 of 20 quadrats) of only a single herbaceous species with $C = 10$ (*Carex albicans* var. *albicans* Willd. Ex Spreng.) and, thus, is not necessarily indicative of high floristic site quality. For woody plants, the highest plot-level C was found in Q1, with a low value $C = 2$ (Table 1).

Results of unconstrained Detrended Correspondence Analysis (DCA) showed clear delineation of most of the ten study plots based on species composition alone (Figure 4). The first three axes cumulatively explained 20% of the total variability of the species dataset. Along the first axis, sparsely vegetated Q1 plot and Q70 plots A and B (with herbaceous vegetation only) are separated from all other plots. Along the second axis, more species-diverse plots also including woody species are separated into two groups: plots at the Q70 quarry top (F–H) and quarry floor (C–E). Site F differs from other Q70 quarry top plots G and H due to the sporadic presence of just a single herbaceous species in the understory (Table S3). The plant community at UF reference plot was similar to those plots at the Q70 quarry floor (C, D) and platform (E) with dense woody understory.

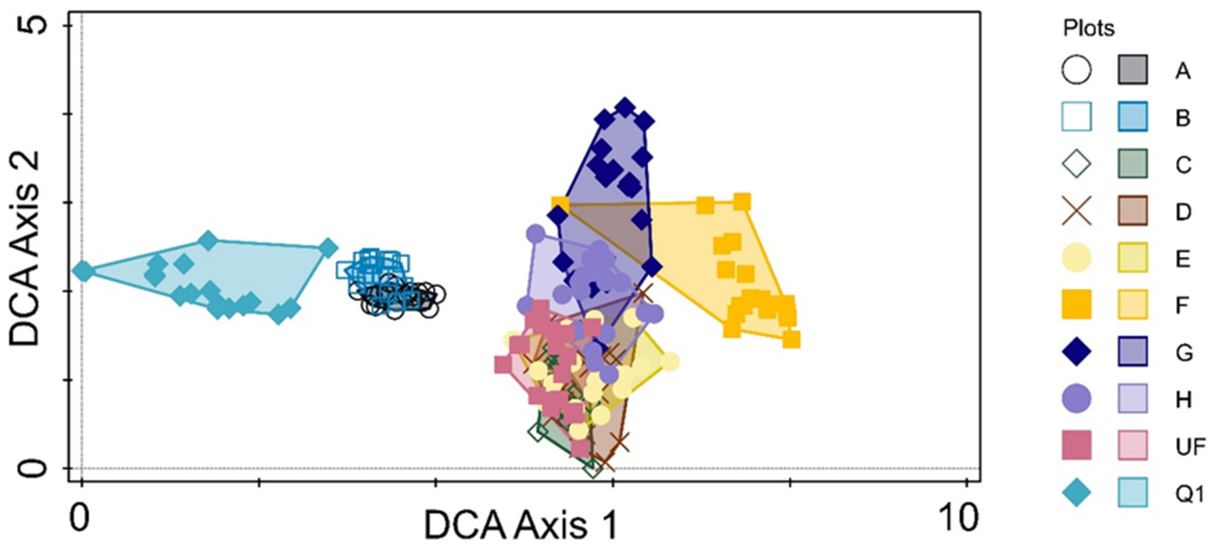

Figure 4. Detrended Correspondence Analysis (DCA) of 82 plant species (after down weighting of rare species) in 200 sample quadrates in 10 plots in a quarry abandoned 70 years ago (plots A–F on quarry floor, F–H on quarry top), in a recently decommissioned quarry (Q1) and an urban forest (UF). Separation of plots along the first and second axes indicated distinct understory vegetation communities at the quarry floor without tree canopy (plots A, B) and at the edge of the quarry top (plots F–H).

In the CCA, with explanatory soil variables and plant species composition and cover in 200 quadrats as response data, the first two axes cumulatively explained 11% of the variation in the response data. That is, of the total variation in plant species cover data explained by environmental data (19.5%), the first two axes explained 56%. Of the 12 significant soil variables included in the analysis (Figure 5a), bulk density, pH, and Mn concentrations were mostly correlated with Axis 1 ($R^2 > 0.69$), P and Ca concentrations were mostly correlated with Axis 2, and Cu with Axis 3; the other variables were correlated about equally with Axis 1 and 2. Not surprisingly, quadrats at Q1 had soils with the highest bulk density, gravel content, pH, and magnesium concentrations. Plots at the Q70 quarry top (F–H) are found at the opposite end of this gradient, with plots on Q70 quarry floor (A–E) being intermediate. The UF reference plot was book ending Q70 quarry floor, but not Q70 quarry top plots on Axis 1 (Figure 5a). Both UF and Q1 bookended Q70 only on Axis 4 that is correlated with Fe and P concentrations (highest in UF) and Ca (highest in Q1) (Figure A1).

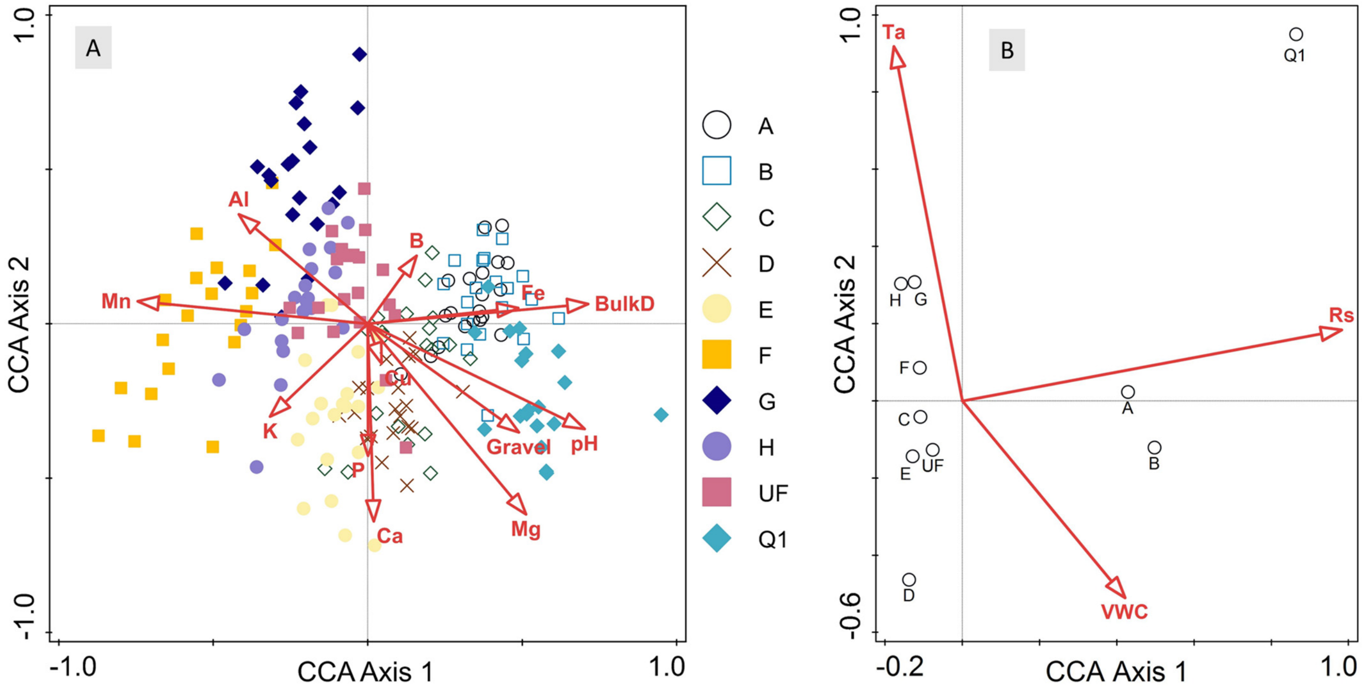

Figure 5. Canonical Correspondence Analysis (CCA) ordination diagrams (biplots) showing delineation of quadrats (**A**) and plots (**B**) based on plant species composition as explained by environmental variables in eight plots (A–H) within the 70-year-old abandoned quarry (Q70) and in the reference plots at an urban forest (UF) and a recently decommissioned quarry (Q1) in Jefferson City, Missouri, USA. Symbols in (a) show the 200 quadrats in which soil variables were measured; in (b) quadrat-level species data had been averaged to the plot-level to match the scale of microclimate measurements. The arrows point toward the direction of the steepest increase of values of environmental variables; the coordinates of an arrow tip are correlations of the environmental variable with the two ordination axes (e.g., bulk density is highly correlated with Axis 1, but there is almost no correlation with Axis 2). UF separates from the other sites along the 4th ordination axis (Figure A1).

When conducting a CCA with plant species data averaged across the 20 quadrats per plot, the reduction of noise in the resulting plot-level dataset led to the first two and three axis explaining 36 and 41%, respectively, of the variability in species composition and cover. With ten plots in the dataset, only three environmental variables could be included in a constrained analysis. Thus, among the six microclimate variables recorded at the plot level, those highly correlated with another were omitted. Those omitted were RH ($R^2 = -0.95$ with Ta), Ts ($R^2 = 0.81$ with Ta), and EC ($R^2 = 0.81$ with VWC). Using forward selection among the three remaining variables, Rs and Ta explained significant variation in the vegetation data among plots ($p = 0.006$ and 0.02, respectively), but VWC did not ($p = 0.55$).

Separation of the ten plots along Axis 1 was correlated with shortwave radiation ($R^2 = 0.99$) (Figure 5b); expectedly, it was highest at the open plots of Q1 and plots A and B at Q70. Plots with vegetation above 1.1 m (i.e., the height of the radiation sensor) had the lowest shortwave radiation (Figures 3l and 5b). Along Axis 2, plots are characterized by differing mean growing-season air temperature (correlation Axis 2 with Ta: $R^2 = 0.85$) with Q1 and plots at Q70 quarry top having the highest values. Plots on Q70 quarry floor had the lowest Ta. UF, with a NE aspect, had intermediate mean Ta (Figure 5b). VWC, while not statistically significant, was correlated with Axes 2 and 3 ($R^2 > 0.6$). With only three explanatory variables in the analysis, the first three ordination axes explain all the variation in the fitted response data.

4. Discussion

The abandoned limestone quarry investigated in this work provided a unique opportunity to assess long-term outcomes of spontaneous succession using an array of microsites differing in abiotic conditions. While mining legacy effects were still detectable in soil characteristics, especially physical characteristics like bulk density and gravel content, current microclimate was shaped by a combination of mining legacy and present-day vegetation characteristics. Low levels of P, K, Fe, and Mn, common in limestone quarries [32,54] due to the composition of the parent material and high pH, had been somewhat alleviated after 70 years of recovery but still explained variation in the plant community composition. While low fertility levels and other abiotic factors are generally seen as obstacles to spontaneous recovery [16], low-nutrient conditions may be key to establishment and long-term survival of species and communities that are poor competitors [20]. For example, fertilization studies in limestone quarries generally show greater biomass [27,32] at the expense of diversity [55]. The availability of nitrogen, an important macronutrient, was not measured in this study. Given that soil and sizable trees were present at the quarry floor after 70 years of quarry recovery, it may be reasonable to assume that internal nitrogen cycling (i.e., driven by decomposition at the site) had been well established by that point. Recovery may also have been influenced by atmospheric deposition of N, which resulted in inputs of about 5 kg N ha^{-1} y^{-1} between 1981 and 2010 near the study site [56]. However, the interaction of quarry revegetation and atmospheric nutrient inputs have not been explored.

In this study, interrelated soil physicochemical characteristics like bulk density, gravel content and pH, and microclimate characteristics of shortwave radiation and air temperature were the most important factors, of those measured, in determining understory vegetation composition. Surprisingly, VWC was not a significant variable. This is likely a consequence of progressed soil formation and the generally high annual precipitation in the region; it is also possible that high variability in VWC measurements resulting from lack of contact of the soil probe with the soil during times of dry soils limited the predictive power of the variable. Overall, the environmental variables explained only a small fraction of the variability observed in the species composition and abundance. One explanation is that, with progressing succession, the importance of abiotic factors diminishes, and biotic factors become predominant in shaping plant communities [57]. Additionally, a high degree of noise (stochastic variation) is common in the analysis of vegetation communities [58]. Noise in the vegetation composition data may be due to dispersal, i.e., different species may be found at similar locations simply by arriving there first [59,60], not due to a causal effect of environmental conditions. Regardless, 70 years after abandonment, the plant assemblages in the eight Q70 plots were still distinct, supporting the forming consensus that refraining from traditional reclamation approaches allows a disturbed surface mine to maximize its ecological potential through natural succession [20].

As shown in previous studies [25], the absence of a closed tree canopy promotes a diverse herbaceous layer. In plots A and B of Q70, the absence of woody plants was supported in the past by episodes of "brush clearing" (M. Schleer, Lincoln University archivist, personal communication) and at the time of the study by occasional mowing. High herbaceous species richness was also aided by high-light environments created by topographic edges, like those on the cliff edge of plots G and H and the pond edge of plot E. The persistence of these edges can promote herbaceous plant diversity potentially in perpetuity, despite the closed canopy above it. Understory species richness in Q70 plots (median 29) generally surpassed that of undisturbed reference site UF (22); however, only one UF plot was included in the study precluding firm conclusions from this comparison. For context using natural communities in Missouri, in the forests of the Missouri Ozarks

33–67 understory species were identified in 32-m^2 plots [61], and at Prairie Fork Conservation Area, 70 km from Jefferson City, 32–68 species were found in 25-m^2 areas in forested and non-forested plots [62]. Thus, in the current investigation, understory species richness in the naturally regenerated quarry seems to have reached the lower range of natural, high-value habitats.

Seventy years after abandonment, 42 native herbaceous species and 30 native woody species had colonized the quarry area, but there were also 21 non-native species. While this work supports the finding that over longer time periods dispersal limitations are not an issue, as mining sites act as seeds traps [20], it highlights concerns that non-native species have the potential to quickly establish in disturbed areas [15]. In the recently decommissioned quarry (Q1) and the treeless plots on the quarry floor of Q70, both a significant number of species and proportion of cover was from non-native species. This likely reflects the prevalence of non-native species in the surrounding urban and agrarian (pastureland) matrix, rather than a primary consequence of past quarrying activity creating bare surface. This is evidenced by woody nonnatives, mostly bush honeysuckle species, that are as common in the UF as in Q70. Thus, management of non-native invasive species (especially prolific dispersers like honeysuckles) might be required [63] during spontaneous succession of disused quarries.

Considering concerns of potentially long timeframes associated with natural regeneration, the onset of succession at the study site was swift, as indicated by plants found on mined surfaces one year after decommissioning the limestone quarry (Q1). The age of woody vegetation on the quarry floor of Q70 showed that the first trees successfully established within a decade of abandonment, following a similar timeline as observed in other abandoned surface mines (e.g., [64]). After 70 years of succession, tree basal area at the quarry floor was not different than some plots on the quarry top, despite harsher initial growing conditions, like coarse substrate, high pH, or lower soil water, that are still detectable after 70 years. This study also showed that, while Q1 obviously bookended conditions at Q70 by representing the starting point, the UF represented a different state not replicated by any one of the eight Q70 plots at the time of study. While abiotic conditions of Q70 quarry top were similar to those in UF (as non-quarried surface), plant communities were not. Thus, cliff edges at the quarry top represent unique habitats giving rise to unique understory plant communities that differ from those found in forest interior.

Study Implications

Current Missouri Law 444.774 on Reclamation Requirements and Conditions states that decommissioned surface mine lands must be graded to a rolling topography, whereby a maximum of 25% of the area can be left ungraded if designated for wildlife use [40]. It also states that mine operators shall seed or plant the area with grass, legumes, shrubs or trees in accordance with reclamation goals. However, unlike coal mine surfaces with the potential for long-term persistence in a bare soil stage due to extreme (low) pH and (high) C:N ratio (i.e., low nutrient availability), decommissioned limestone quarries have more favorable substrate conditions and, consequently, faster spontaneous recovery rates [65]. Therefore, in urban areas, if public safety concerns are met (e.g., through fencing), no active reclamation is necessary to achieve the goal of reestablishing near natural vegetation communities. Alternatively, a hybrid approach involving the backfilling of potentially dangerous features (e.g., cliff walls), followed by natural succession should be considered. To improve visual appeal, the periphery of the decommissioned surface mine could be more quickly reclaimed though ameliorating the substrate and planting fast-growing pioneer species, a common approach to reclaiming marginal lands left after mining operation [66], while the interior areas are left to revegetate on their own. However, in urban environments where colonization potential by valuable native species may be limited, introducing propagules from natural areas (e.g., via herbaceous clippings [16,33]), may counter a possible dominance of invasive species that are pervasive in urban areas.

5. Conclusions

With >100,000 km^2 globally impacted by surface mining at present, and with increasing demand for surface-mined products, land managers are challenged to address landscape degradation and visual impacts of disused quarries, especially in urban areas.

The results of this case study from a small Missouri dolomite limestone quarry abandoned 70 years ago are congruent with the growing body of studies on spontaneous succession on abandoned surface mines worldwide in that spontaneous (vs. managed) revegetation can lead to species-rich, near-natural communities. This is aided by persistent topographical features of the post-mining landscape, giving rise to an array of microclimates and vegetation communities. In this study, over 94 herbaceous and woody understory species were present in the study area with trees establishing on mined surfaces within the first decade of abandonment. This diversity was supported by site conditions representing a spectrum from resembling recently mined conditions to natural conditions regarding soil physicochemical characteristics and microclimate. While different geographic regions have different hydro-climatic controls that impact speed and outcome of natural regeneration, land managers should embrace post-mining landscapes as opportunities for conservation. The ecological benefits derived from minimal intervention after mining operations cease and the cost savings to mine operators or taxpayers represent a win-win situation. This warrants a revision of current legislation requiring technical reclamation on sites with favorable substrate, such as limestone. However, any new legislation should consider securing funding for long-term management of invasive species in quarries allowed to undergo spontaneous revegetation. Future research should be directed toward monitoring the temporal pattern of soil, hydro-climate, and vegetation recovery to determine the point in time at which human intervention is no longer required.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12010117/s1, Table S1: Soil physical and chemical characteristics in eight plots of a 70-year-old abandoned quarry (Plots A–E: quarry floor, F–H: quarry top), a recently decommissioned reference quarry (Q1), and an urban forest reference site (UF). Study sites are located in Jefferson City, Missouri, USA. Values represent the mean and standard deviation (SD) of 20 measurements per plot. BulkD—bulk density in g cm^{-3}; Silt/Clay, Sand and Gravel represent particle size distribution in %; element concentrations are in mg per kg of dry soil; Table S2: Microclimate in eight plots of a 70-year-old abandoned quarry (Plots A–E: quarry floor, F–H: quarry top), a recently decommissioned reference quarry (Q1), and an urban forest reference site (UF). Study sites are located in Jefferson City, Missouri, USA. Values are based on daily data (with each data point representing the mean of 24 hourly values) collected from 1 May—30 September 2011. Rs—shortwave solar radiation, Rh—relative humidity, Ta—air temperature, VWC—volumetric soil water content, Ts—soil temperature, EC—soil electric conductivity., Table S3: Species cover (dm^2 m^{-2}, %) in each study plot: Q1—recently decommissioned quarry, A–E—quarry floor and F–H—quarry top of a quarry abandoned 70 years ago, and UF—urban forest in Jefferson City, Missouri, USA. Highlighted fields denote the three species <1 m in height with the greatest cover in each plot. Nomenclature is from Steyermark's Flora of Missouri; common names are from the Flora of North America if they were not given in the Flora or Missouri. *C* is the Coefficient of Conservatism; an asterisk with a value of 0 for C indicates an exotic species.

Author Contributions: For the current work, author contributions were as follows: conceptualization, K.S. and J.A.H.; Formal Analysis, K.S. and J.A.H.; Investigation, K.S.; Data Curation, K.S.; Writing—Original Draft Preparation, K.S. and J.A.H.; Writing—Review and Editing, K.S. and J.A.H.; Supervision, K.S.; Project Administration, K.S.; Funding Acquisition, K.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on reasonable request from the corresponding author or are available through publicly available sources noted in text.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

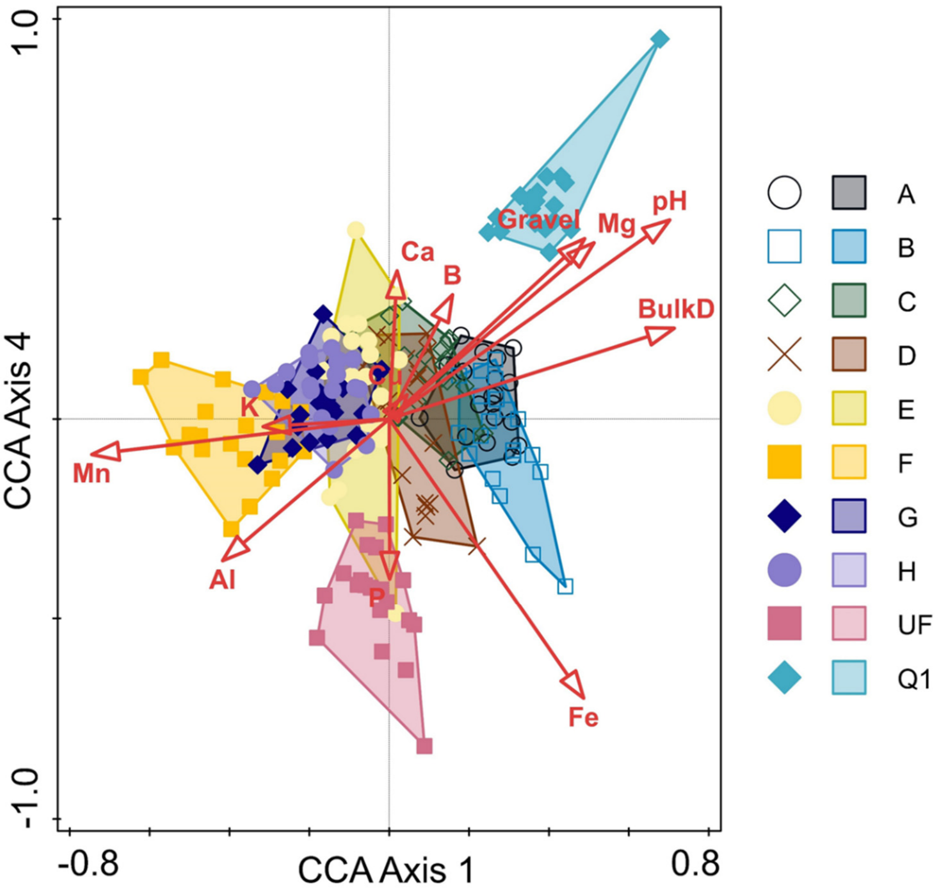

Figure A1. First and fourth axes of Canonical Correspondence Analysis (CCA) ordination diagram showing delineation of quadrats based on plant species composition as explained by environmental variables in eight plots (A–H) within the 70-year-old abandoned quarry (Q70) and in the reference plots at an urban forest (UF) and a recently decommissioned quarry (Q1) in Jefferson City, Missouri, USA. Symbols show the 200 quadrats in which soil variables were measured. The arrows point toward the direction of the steepest increase of values of environmental variables; the coordinates of an arrow tip are correlations of the environmental variable with the two ordination axes (e.g., soil P concentration is highly correlated with Axis 1, but P does not correlate with Axis 2). Separation of plots along the first axis indicated distinct understory vegetation communities at the quarry top and the quarry floor. UF also has distinctive understory as seen by separation along the 4th axis.

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