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Research article

Mining methods exert differential effects on species recruitment at artisanal small-scale mining sites in Ghana

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A B S T R A C T

Artisanal small-scale mining (ASM) is one of the essential rural non-agricultural livelihood activities in Ghana. However, basic and rudimentary practices and tools associated with ASM activities lead to vegetation and soil destruction. Given the limitation of state-sponsored reclamation of abandoned ASM sites, the role of natural recovery in abandoned mine sites is deemed a viable option, as it lowers financial obligations, promotes pioneer species and improves local ecology. The residual impacts of different ASM methods (alluvial or chamfi) and their implications for reclamation are less explored. Using a randomised sampling approach, one hundred and eight (108) plots representing 54 abandoned mined (27 alluvial and 27 chamfi) and 54 unmined areas (control plots) were demarcated for seedling and sapling assessments. A total of 6,157 seedlings belonging to 133 species and 4,536 saplings belonging to 42 species were recorded. Pielou's evenness and Shannon indices showed that both seedlings and saplings were equitably distributed between mined-out sites and their controls for both methods but showed evidence of environmental variability. This variability was more conspicuous in chamfi mined-out sites, confirming some degradation impacts. *Chromolaena odorata* (L.) and *Mimosa pudica* L. were the dominant seedlings recorded, while *Hymenostegia afzelii* (Oliv.) Harms and *Musanga cecropioides* M. Smithii R. Br. dominated the saplings. The alluvial method exerted a far greater effect on stand features such as basal area and stand density for saplings owing to its greater soil damage. Assisted restoration measures directed at abandoned mined sites can facilitate ecosystem recovery to a trajectory reminiscent of that of nearby undisturbed forests.

1. Introduction

The artisanal and small-scale mining (ASM) method is one of the essential rural non-agricultural livelihood activities in the developing world, providing jobs for millions of people directly and indirectly (Hilson, 2016). ASM involves exploiting mineral deposits using basic or rudimentary tools and primitive mining and processing techniques (Bansah et al., 2016). In Ghana, ASM has become a significant contributor to the economy, mainly to local communities where they are predominantly practised (Kumi-Boateng and Stemn, 2020; Banseh et al., 2016). The Minerals Commission of Ghana estimates that over a million Ghanaians are engaged in ASM operations (Bansah et al., 2016, 2018), of which approximately 85% are illegal (Kumi-Boateng and Stemn, 2020). However, only an estimated 10% of ASM activities operate legally and formally in Ghana (Ofosu et al., 2020; Owusu-Nimo et al., 2018).

ASM comes in different types, differentiated based on the methods of operation (Bansah et al., 2016; Mantey et al., 2017; Mensah, 2015). The study by Mantey et al. (2017) characterised the operational dynamics of ASM hotspots in Ghana and noted five broad methods: Placer/alluvial, underground/hard rock, surface (chamfi), mill-house, and selection (pilfering). These methods have differentiated impacts on the environment and are predominantly characterised by unfilled pits, landscape disturbance, and destruction of plant cover and community structure (Mantey et al., 2017; Edwards et al., 2014). Each of these methods relates vegetation removal with cascading effects on the environment (Essandoh et al., 2019; Bansah et al., 2016; Edwards et al., 2014).

Generally, species recruitment on an abandoned goldmine is uncertain because soil structure and hydrology are immensely compromised by mining activities (Essandoh et al., 2019; Liu et al., 2017). This situation is greatly confounded by the types of ASM methods used, altering floristic

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attributes such as species diversity and composition (Valois-Cuesta and Martínez-Ruiz, 2016). While the chamfi method involves relatively shallow removal of plant life and topsoil and is considered fairly environmentally safe for plant colonisation, other factors, such as soil compaction caused during operations, could offset the recovery pattern of species (Owusu-Nimo et al., 2018). In contrast, the application of relatively heavy machinery with the alluvial method makes their damage to plant life and soil structure far more pronounced (Batey, 2009). Despite the differences in operational guidelines (see Table 1) for adopting either of the two methods, their impacts on existing vegetation are not disputed. These impacts on vegetation dynamics threaten local endemic biodiversity and consequently alter the composition and irreplaceable functional species (Horváth et al., 2019; Alroy, 2017; Jarsjö et al., 2017).

As the alluvial and chamfi ASM methods soared across many mining communities in Ghana (Kumi-Boateng and Stemn, 2020; Bansah, 2019; Essandoh et al., 2019), one key question yet to receive enough attention is whether abandoned mined sites could naturally regenerate to drive ecological succession. Succession, therefore, is a major ecological occurrence that underpins species recovery following disturbance (Prach and Walker, 2011). Disturbance essentially creates an environment for light-demanding pioneers to establish and persist, thus contributing to the overall species diversity in disturbed areas (Bongers et al., 2009). However, it is also known that too much disturbance also reduces the overall species diversity by eliminating late succession species (Chapagain et al., 2021). While succession studies have been conducted within the context of forest ecosystems following various disturbances in Ghana (Damptey et al., 2021; Swaine and Hall, 1983), that of disturbances associated with mining is very minimally researched. It is particularly unclear how early successional species colonise abandoned mined sites and the extent to which the variations in soil disturbance associated with different methods of illegal ASM influence vegetation occurrence and associated dynamics.

Furthermore, despite the widely documented effects of mining on water bodies (Yirenkyi, 2021; Macdonald et al., 2015), biodiversity (Takyi et al., 2021; Adesipo et al., 2020; Damptey et al., 2020) and other social vices (Arah, 2015; Ofosu et al., 2020), studies that seek to delve deep into the effect of different mining methods on ecological succession are limited in Ghana. Hence, the assessment of changes caused by specific ASM methods to functional floral resources at the local and landscape levels could help devise strategies for post-mining site rehabilitation.

We seek to unravel the effect of the various mining methods independently on early vegetation dynamics after site abandonment. Specifically, we aim to determine (1) species diversity (both seedlings and saplings) and composition of sites previously mined with either chamfi or alluvial methods, as well as documents the characteristic site-species association and (ii) stand structural characteristics of each site compared with their undisturbed control sites. Generally, based on the nature of machinery used for mining in each method, we anticipate the effect of mining on vegetation dynamics to be far more pronounced in the alluvial than in the chamfi.

Table 1. Characteristics of each ASM method in terms of approach, impacts on soil, and key tools employed in their respective operations (Mantey et al., 2017).

Mining Types	Impacts on soil	Approach	Key materials/ tools used
Chamfi	Mostly done rudimentarily and manually using shovels, pickaxes, earth chisels, and other simple equipment with minimal soil impact	This occurs typically in land-locked areas, either near or far from water bodies. However, requires water for simultaneous mining and the gold extraction process	Diesel-powered engine, retort, pans, shovels, pickaxe
Alluvial	Soil impact is extensive with the use of heavy-duty machines like excavators, dozers, and loaders.	It takes place with simultaneous mining and gold extraction process. It mainly occurs in wetland areas, rivers/ creeks/streams banks.	Sluice board, washing plant/ trommel, Excavator, dozer, loader

2. Materials and methods

2.1. Study area

The study was carried out in three districts: Amenfi Central, Tarkwa Nsuaem, and Prestea Huni Valley, all in the Western Region of Ghana. Amenfi Central is located between latitudes 5°37′59.52″N and longitudes 2°15′4.32″W; Tarkwa Nsuaem is located between latitudes 40́501 N and 50́401 and longitudes 10́451 and 2́W, while Prestea Huni Valley is also located between latitudes 5° 34′ 32″ N and longitudes 2° 0′55.8″ W (Figure 1). The study area falls within the wet semi-equatorial climate zone of Ghana. The climate is tropical, with a double maxima rainfall pattern, namely a major season (March to August; characterised by heavy rains) and a minor season (September to November; characterised by frequent showers).

The western region was chosen for this study because it represents the most active mining region in Ghana, having the largest concentration of large-scale gold mining companies (LSMs) and both regulated and unregulated ASMs (Mantey et al., 2017). Therefore, in selecting the districts of interest, towns with ASM activities were visited to identify sites that were mined previously and have been abandoned for some years. Such mine sites were purposively sampled based on attributes such as the years they were abandoned after the mining activities, the presence of vegetation, and their easy accessibility to permit sampling. Areas with uncovered mine pits were excluded from sampling for safety reasons. In selecting such sites, the type of methods and machinery employed during the mining period were also considered and categorised (Table 1) as well as their sizes (at least 5 ha). All sites selected for sampling had been abandoned for at least four years with no ongoing mining activity. The four-year interval was to guarantee some degree of vegetation recolonisation after mining. An unmined area was additionally demarcated for each site to serve as a reference (control) ecosystem for comparison. Selected reference sites were usually secondary forests with minimal to intermittent disturbances but with no mining activities of any sort. Such reference sites usually had a sizable area (at least 5 ha) and were located at most 1 km from the mine sites.

2.2. Sampling

In a reconnaissance survey, one hundred and eight (108) plots were identified and demarcated for assessment. During the reconnaissance survey, we identified and interviewed miners in the various communities to determine the time since the last abandonment of the mining site. After the interview, it was identified that the mined areas had been abandoned for four (4) years, and accessibility to these sites was not an issue. All identified areas were marked and demarcated for further assessment. Using purposive random sampling, the study plots (20 × 20 m) were demarcated, each with two subplots (1 m^2, and 5 m^2). In the 1 × 1 m subplots, all individuals of herbs, vines, grasses, and woody species less than 2.5 cm in diameter and within their early growth/first year with their first cotyledonary leaves were recorded and grouped as seedlings.

Furthermore, in the 5 × 5 m subplots, all established woody species with a diameter at breast height (dbh @ 1.3 m) between 2.5 and 5 cm were recorded as saplings. For each sampled plot, species were identified onsite with vegetation manuals (e.g., Hawthorne and Gyakari, 2006) by a local botanist with the assistance of experienced forest guards, and their corresponding diameter was measured and recorded. Where onsite identification was not possible, leaf samples were pressed and taken to the herbarium for identification by a botanist. No vegetation survey was conducted on dug-out areas covered with mud and/or water. Adjacent undisturbed areas with an intact ecology and higher functionality than the ecosystem of the identified mined-out sites were selected as reference systems for comparison.

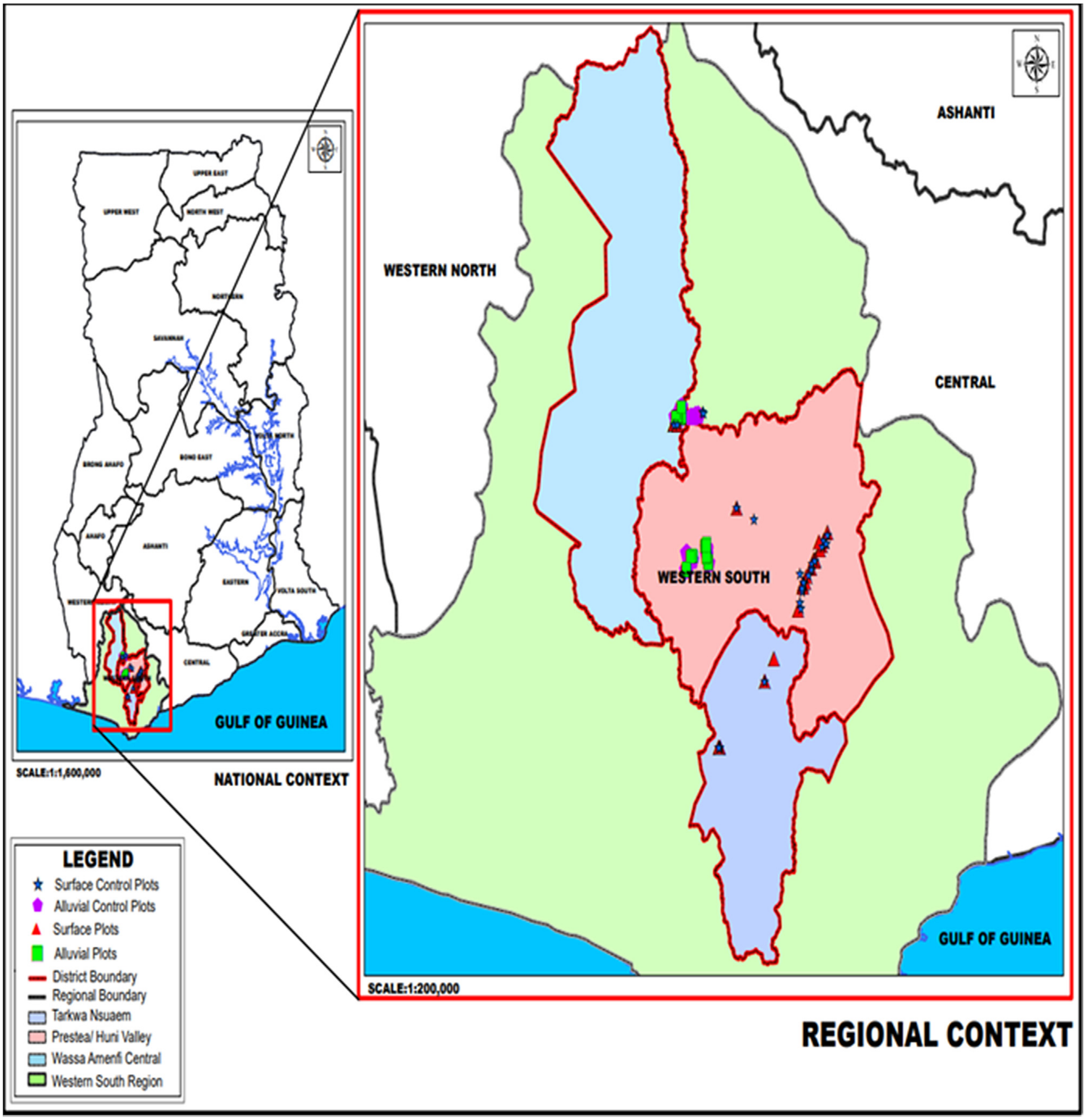

Figure 1. Study area map showing the three districts in the region and the sampling sites for both mined and unmined (control) plots.

2.3. Data analyses

After verifying normality using the Kolmogorov-Smirnov (K–S) test, the dataset was further log-transformed (log (X+1)) for further analysis. Based on the log-transformed data, diversity indices (Pielou's evenness, Shannon; Pielou, 1966; Shannon and Weaver, 1964) were estimated using the "Diverse" function in Primer vs 7. Significant differences between the sites for the measured tree attributes were evaluated with one-way analysis of variance (ANOVA). The statistically significant differences in tree community composition between sites were estimated with a one-factorial permutational analysis of variance (PERMANOVA) using Euclidean distances and unrestricted permutation of raw data (N = 9999 (Anderson et al., 2008). Patterns in community composition between sites and their controls were visualised with non-metric multidimensional scaling (nMDS) analysis. Each site's characteristic tree species were further overlaid as vectors (correlation = 0.4) on the nMDS cluster. The goodness of fit of the nMDS ordination was evaluated using a stress value (Clarke et al., 2014). Finally, a similarity percentage analysis (SIMPER) was used to estimate tree species contributions to the observed dissimilarities for seedlings and saplings between the sites based on a 70% cut-off for lower taxonomic contribution (Clarke, 1993). All statistical analyses and visualisations were carried out with either the Plymouth Routines in Multivariate Ecological Research (PRIMER vs 7, with PERMANOVA add-on; Clarke and Gorley, 2015) or R software vs 3.6.1 (R Core Team, 2019).

3. Results

3.1. Seedling and sapling species diversity

A total of 6,157 seedlings belonging to 133 species and 347 saplings belonging to 42 species were recorded (Table 2). Seedling richness was highest in the main chamfi plots, followed by the alluvial main plots, chamfi control plots, and alluvial control plots. For saplings, richness was higher in the chamfi control and lowest in the alluvial control.

In terms of seedling diversity, Pielou's evenness revealed no statistically significant difference between the chamfi main and control plots ($p > 0.05$). Shannon indices, however, differed significantly for the chamfi main and control plots ($p = 0.011$). For the alluvial plots, Pielou's evenness showed significant differences ($p = 0.001$) between the main and control plots. Shannon's indices were, however, not significantly different when the two sites were compared ($p = 0.609$).

For saplings, Pielou's evenness was not significantly different when chamfi main and control plots were compared. However, Shannon's indices differed significantly for the chamfi main and control plots ($p = 0.001$). For the alluvial plots, only Shannon's indices significantly differed between the main and control plots ($p = 0.011$). Significant differences in seedling and sapling richness and abundance were observed for the alluvial main and its control plots and chamfi main and control plots ($p = 0.001$).

3.2. Seedling composition

Seedling species composition differed significantly between the chamfi main and control plots ($F_{1,268} = 11.36$; $p = 0.001$) and the alluvial main and control plots ($F_{1,268} = 14.82$; $p = 0.001$). Two distinct clusters were observed for seedling composition between the alluvial main and control plots (stress value = 0.09; Figure 2A). The alluvial main plots were characterised by the abundance of *Chromolaena odorata* (L.) (40%), *Mimosa pudica* L. (14%), *Alcorhnea cordifolia* (Schum. & Thonn.) Müll.-Arg. (13%) and *Baphia nitida* G. Lodd. (5%). In comparison, the control plots were mainly dominated by *Chromolaena odorata* (L.) (33%), *Aspilia africana* (Pers.) C. D. Adams (18%), and *Panicum maximum* Jacq. (9%).

The seedling species composition for the main chamfi plots was also separated from that of the chamfi control plots (stress value = 0.12; Figure 2B) and was characterised by the abundance of *Mimosa pudica* (31%), *Chromolaena odorata* (30%), *Musanga cercropioides* (5%), and *Panicum maximum* (5%). The control plots were also characterised by the abundance of *Chromolaena odorata* (30%), *Aspilia africana* (27%), *Alcorhnea cordifolia* (10%), and *Waltheria indica* L. (6%).

An average dissimilarity of approximately 90% was observed between the seedling composition of the chamfi main and the control plots, with only 15 species contributing approximately 50% to the above dissimilarity (Table 3). Higher abundances of *Mimosa pudica* L., *Panicum maximum* Jacq., *Centrosema pubescens* Benth., *Euphorbia hirta* L., *Passiflora foetida* L., *Chromolaena odorata* (L.), *Musanga cercropioides* M. Smithii R. Br., *Emilia coccinea* (Sims) G. Don, *Ipomoea aquatic* Forssk., *Dialium guineense* Willd., and *Dissotis rotundifolia* (Sm.) Triana were observed in the main chamfi plots compared with the control plots. *Aspilia africana* (Pers.) C. D. Adams, *Alcorhnea cordifolia* (Schum. &Thonn.) Muell. Arg., *Waltheria indica* L., and *Justicia flava* T. F. Daniel were more abundant in the control plots than in the main plots. *Emilia coccinea* (Sims) G. Don, *Ipomoea aquatic* Forssk., and *Dissotis rotundifolia* (Sm.) Triana were absent from the control plots.

For the seedling composition of the alluvial main and the control plots, an average dissimilarity of 89% was observed. Fifteen species cumulatively contributed about 52% to the above dissimilarity. Except for *Alcorhnea cordifolia,* which was completely absent in the control plots, the remaining 14 species were found in the two alluvial main plots (Table 3). Higher abundances of *Mimosa pudica, Alcorhnea cordifolia, Chromolaena odorata, Centrosema pubescens, Baphia nitida, Waltheria indica, Musanga cercropioides, Cola caricaefolia, Flagellaria guineensis, Antiaris toxicaria,* and *Drypetes leonensis* were found in the alluvial main plots than in the control plots. On the other hand, *Aspilia africana, Panicum maximum, Landophia calabarica,* and *Strychnos aculeate* were more abundant in the control plots than in the main plots (Table 3).

3.3. Sapling species composition

The sapling species composition differed significantly between the alluvial main and its control plots ($F_{1,52} = 4.79$; $p = 0.001$, stress value = 0.17; Figure 3A) as well as between the chamfi main and its control plots ($F_{1,52} = 4.62$; $p = 0.001$, stress value = 0.19; Figure 3B). However, some overlaps were observed between some main and control plots of both the alluvial and chamfi sites.

A simper analysis revealed the alluvial control plots to be characterised by the abundance of *Hymenostegia afzelii* (22%), *Musanga cercropioides* (20%), *Baphia nitida* (15%), and *Drypetes leonensis* (12%). The alluvial main plots were dominated by the abundance of *Hymenostegia afzelii* (41%), *Musanga cercropioides* (16%), and *Drypetes leonensis* (14%). The chamfi main plot was characterised by *Musanga cercropioides* (18%), *Rinorea ilicifolia* (10%), *Antiaris toxicaria* (9%), *Pavetta grandiflora* (9%), *Glyphaea brevis* (7%), *Nauclea diderrichii* (7%), *Baphia nitida* (6%) and *Dialium guineense* (6%). The chamfi control plots were also characterised by *Musanga cercropioides* (20%), *Nauclea diderrichii* (13%), *Dialium guineense* (10%), *Antiaris toxicaria* (10%), *Ceiba pentandra* (7%), *Tectona grandis* (5%), *Terminalia superba* (5%), and *Panda oleosa* (5%).

An average dissimilarity of 77% was observed between the sapling species composition of the chamfi main and control plots, with 8 species contributing about 55% to the above dissimilarity (Table 4). All 8 species were more abundant in the control plots than in the main plots, with *Ceiba pentandra* utterly absent in the main plots. An average dissimilarity of 78% was established between the alluvial main and control plots, with just 4 species contributing 55% to the above dissimilarity. All four species were more abundant in the control plots than in the main plots.

3.4. Saplings structural attributes

The sapling basal area differed significantly between the alluvial main and the control plots ($F_{2,52} = 8.13$; $p = 0.005$) as well as between the chamfi main and control plots ($F_{2,52} = 8.74$; $p = 0.004$). Similarly, the alluvial main and control plots ($F_{2,52} = 43.42$; $p < 0.001$) and the chamfi main and their control plots ($F_{2,52} = 20.19$; $p < 0.001$) differed significantly in terms of the density of the tree. However, the average tree

Table 2. Species attributes and diversity indices of seedlings and saplings for the study site (N = 27 per site). CM: chamfi main, CC: chamfi control, AM: alluvial main and AC: alluvial control.

Attributes	Seedlings				Saplings			
	CM	CC	AM	AC	CM	CC	AM	AC
No. of Species	84	64	71	54	21	25	13	12
No. of Individuals	2174	1189	1841	953	56	141	42	108
Diversity indices								
Pielou's Evenness(J)	0.966	0.961	0.961	0.972	0.991	0.985	0.991	0.981
Shannon (H′)	2.724	2.530	2.714	2.263	0.350	1.090	0.270	0.624

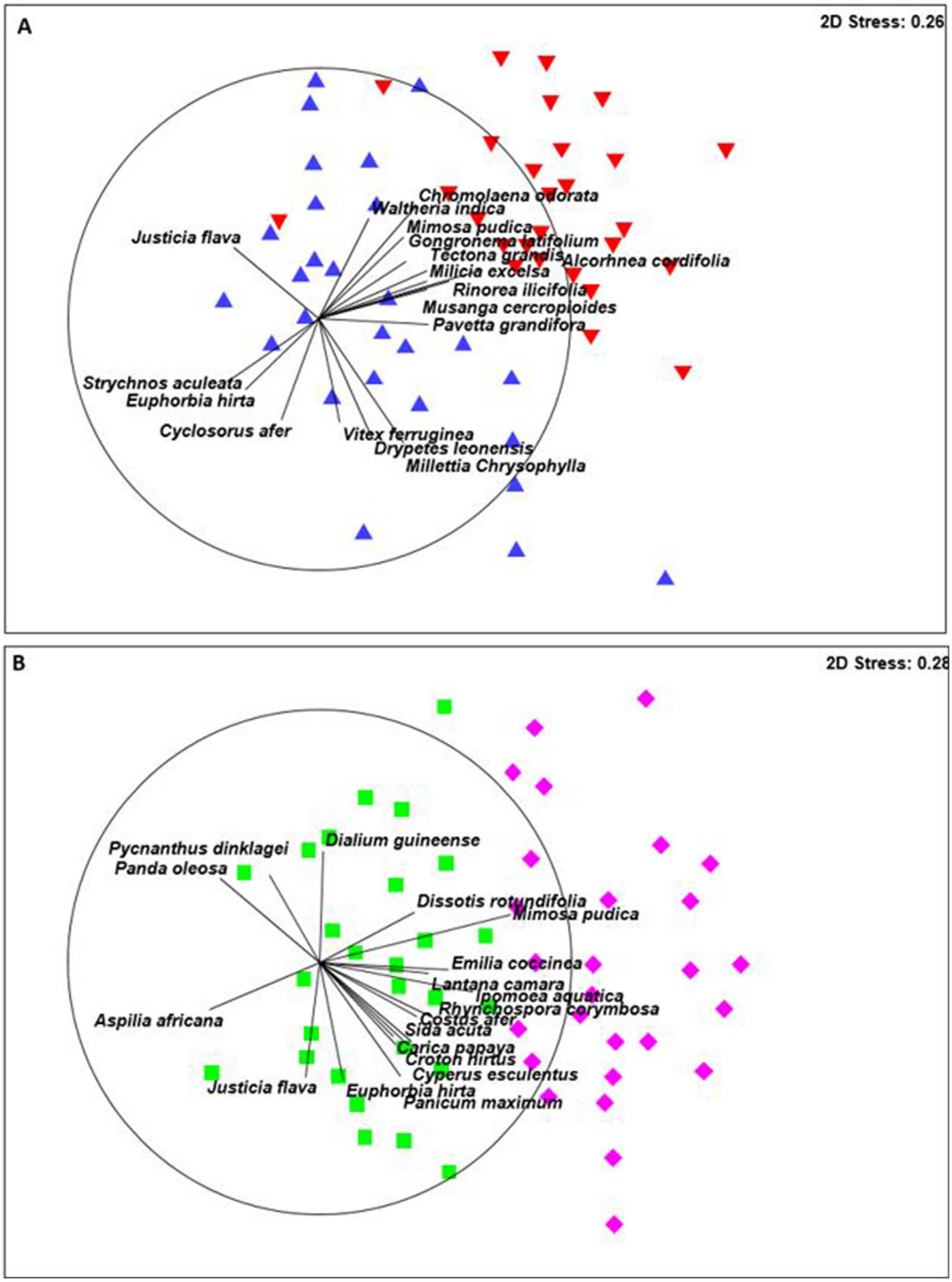

Figure 2. Non-Metric Multidimensional Scaling (n-MDS) ordination of seedling species composition for (A) alluvial (red: control, blue: main) and (B) chamfi (green: control, pink: main) plots (54 sample plots per site). Highly correlated species (correlation at 0.4) for each site and plot are overlaid. The distance between the individual plots and sites reflects the degree of dissimilarity of species composition among plots and sites.

height was not significantly different when the alluvial main and its control plots and the chamfi main and control plots were compared (Figure 4).

4. Discussion

The natural succession of post-mining sites is paramount from a conservation point of view, especially when the system is resilient and can recover quickly after anthropogenic disturbances (e.g., mining). However, the system's ability to self-recover from disturbance depends on several factors, including the extent of damage and the methods used in mining operations (Balke et al., 2014). In this study, we unraveled how two different mining methods (alluvial and chamfi) in Ghana differently influence plant community assembly.

Four years after mining yielded no significant differences in seedling diversity for sites mined with either the alluvial or chamfi method. However, there were differences between the various sites mined with difference methods and their corresponding control plots reflecting the impact of disturbance on seedling recruitment. These mining methods are characterised by the extensive use of heavy machinery with greater

Table 3. Seedling contribution (based on SIMPER) to the dissimilarity between sites A) chamfi main (CM) and chamfi control (CC) and B) alluvial main (AM) and alluvial control (AC) plots. (Av. Ab. = Average abundance, Contr = contribution percentage, Cum = cumulative contribution).

A Species	CM Av.Ab.	CC Av.Ab.	Contr%	Cum Contr%	B Species	AM Av.Ab	AC Av.Ab.	Contr %	Cum Contr%
Mimosa pudica	2.33	0.60	6.33	6.33	*Mimosa pudica*	1.86	0.44	6.16	6.16
Aspilia africana	0.76	1.72	5.08	11.41	*Alcorhnea cordifolia*	1.58	0.00	6.02	12.18
Alcorhnea cordifolia	0.97	1.19	3.61	15.01	*Chromolaena odorata*	2.50	1.61	4.19	16.36
Panicum maximum	1.19	0.82	3.59	18.60	*Aspilia africana*	1.20	1.32	3.94	20.30
Centrosema pubescens	1.08	0.31	3.46	22.06	*Panicum maximum*	0.38	0.98	3.86	24.16
Euphorbia hirta	0.92	0.62	3.40	25.46	*Centrosema pubescens*	0.84	0.32	3.32	27.48
Waltheria indica	0.79	0.91	3.36	28.82	*Baphia nitida*	0.98	0.71	3.17	30.65
Passiflora foetida	1.05	0.28	3.31	32.13	*Landophia calabarica*	0.75	0.76	3.09	33.74
Chromolaena odorata	2.17	1.80	3.14	35.27	*Waltheria indica*	0.66	0.36	2.94	36.68
Musanga cercropioides	1.06	0.94	3.03	38.29	*Musanga cercropioides*	0.76	0.30	2.82	39.50
Justicia flava	0.50	0.55	2.74	41.03	*Cola caricaefolia*	0.59	0.36	2.68	42.19
Emilia coccinea	0.80	0.00	2.59	43.62	*Strychnos aculeata*	0.12	0.70	2.65	44.84
Ipomoea aquaticaa	0.72	0.00	2.53	46.14	*Flagellaria guineensis*	0.59	0.49	2.43	47.26
Dialium guineense	0.58	0.51	2.25	48.39	*Antiaris toxicaria*	0.62	0.36	2.37	49.63
Dissotis rotundifolia	0.60	0.00	2.20	50.59	*Drypetes leonensis*	0.44	0.31	2.06	51.69

impacts on soils and vegetation which are advantageous for the initial stage of community assembly (Chang and Turner, 2019; Denslow, 1980). Disturbances from mining leading to the removal of trees, and vegetation and disturbance to soils usually create heterogeneous canopy structures influencing light availability in the understorey of vegetation and make resources available (viable seeds) for pioneer seedling recruitment (Damptey et al., 2021).

The nature of the mild disturbance nature of the chamfi mining method might have promoted higher initial seedling development and better subsequent growth and survival (Aleksandrowicz-Trzcińska et al., 2014). That is, different disturbance regimes create favourable environmental conditions that facilitate germination and seedling emergence necessary for plant community assembly (Bowd et al., 2021). Our results are commensurate with several other studies that reveal better initial seedling recruitment with different intensities of disturbance (e.g., Chapagain et al., 2021; Damptey et al., 2021; Collins et al., 2001). Comparing the mined sites to their control sites, each (irrespective of the mining method) revealed significantly higher seedling diversity, affirming the positive influence of other abiotic factors such as light on seedling recruitment (Liu et al., 2020; Schönbeck et al., 2015). This is affirmed by the higher dominance of invasive pioneer species such *Mimosa pudica* and *Chromolaena odorata,* which perform well in disturbed landscapes (Mandal and Joshi, 2014). The control sites, however, had a higher density of mature trees with denser canopy structures, restricting the amount of light transmission into the understorey for seed germination and seedling recruitment (kara & Topaçoğlu, 2018).

Seedling composition differed significantly between chamfi and alluvial mine sites and their controls, with two clearly defined clusters demonstrating unique species composition patterns. For the alluvial mine sites, only three species accounted for 67% of the species composition, including *Chromolaena odorata* (40%), *Mimosa pudica* (14%), and *Alcorhnea cordifolia* (13%). The dominance of *Chromolena odorata* was expected for the disturbed sites because *Chromolena odorata* is known to colonise disturbed areas due to their ready availability of seeds and their dispersal mechanisms (Khare et al., 2018; Mandal and Joshi, 2014; Zachariades et al., 2009). In a similar study, Essandoh et al. (2019) revealed that the colonisation of *Chromolena odorata* accounted for 54% of the species composition in abandoned ASM sites in Ghana. Likewise, the dominance of *Mimosa pudica* was expected because of its rapid colonising nature. Accordingly, *Mimosa pudica* is known to colonise disturbed areas such as mining and open grounds (Khare et al., 2018; Rai, 2015; Mandal and Joshi, 2014). The chemicals previously used for mining might have also influenced the rapid colonisation of species such as *Alchorhnea cordifolia* since they colonise and grow well in acidic soils (Friis and Harris, 2013; Mavar-Manga et al., 2008).

Sapling composition similarly differed significantly between the alluvial main and its control as well as between the chamfi main and the control. The composition of the alluvial control was dominated by four species that accounted for 69% of the species composition, including *Hymenostegia afzelii* (22%), *Musanga cercropioides* (20%), *Baphia nitida* (15%), and *Drypetes leonensis* (12%). On the other hand, the alluvial main sites were dominated by three species, which accounted for 71% of the species composition, including *Hymenostegia afzelii* (41%), *Musanga cercropioides* (16%), and *Drypetes leonensis* (14%). Interestingly, these three species were also found in the control sites, suggesting that the sapling composition in the disturbed site might have mimicked the composition of the control sites because they were minimally impacted during mining activities, and one was in early succession. All four species, including *Baphia nitida,* which was only present in the control site, are light-demanding pioneer species native to tropical Africa and Ghana with widespread distribution in areas of mature secondary forest regrowth, a characteristic that defines the control site (Damptey et al., 2021).

Stand structure characteristics enable predictions of forest growth and act as indicators for determining the spatial distribution of plant species (Couteron et al., 2005). Our study focuses on sapling structural characteristics such as basal area, density, and height of stands. Greater stand structural attributes indicate good performance of the community, which is mainly characterised by mature trees with heterogeneous canopy cover (Angelini et al., 2015). This implies that saplings with high stand attributes have the potential to transition into a high-performance tree stand as they develop deep roots that can tap water and nutrients from the soil (Giambelluca et al., 2016; Estrada-Medina et al., 2013; da Silva et al., 2011). In comparison, the chamfi sites were less degraded than the alluvial sites which is reflected in the basal area estimates, with chamfi sites recording higher basal area values than the alluvial sites for both the main and control plots. This could be attributed to the different species with a higher inclination to grow larger and faster at the disturbed sites, particularly species affected by mining activity. Similar results have been found from studies on tropical forests subjected to disturbances (Kumar et al., 2006; Nath et al., 2005; Tripathi et al., 2010; Upadhaya et al., 2004). Tripathi et al. (2010) and Pare et al. (2009) found a similar pattern and attributed the high basal area for disturbed forest compared to undisturbed forest to the increase in light intensity as well as decreased interspecific and intra-specific competition for available soil resources in the gaps created by disturbances.

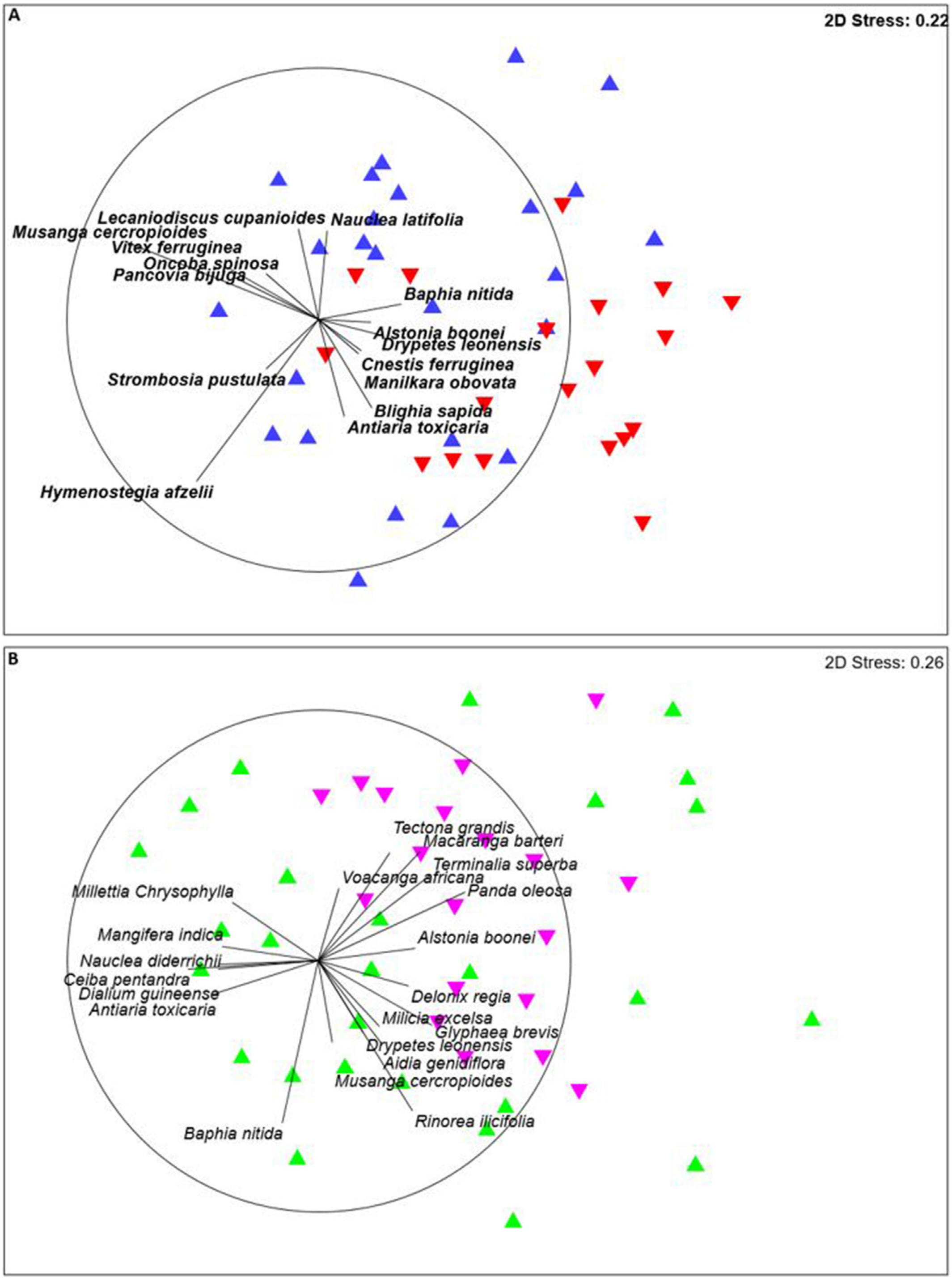

Figure 3. Non-Metric Multidimensional Scaling (n-MDS) ordination of sapling species composition for (A) alluvial (red: control, blue: main) and (B) chamfi (green: control, pink: main) plots (54 sample plots per site). Highly correlated species (correlation at 0.4) for each site and plot are overlaid. The distance between the individual plots reflects the degree of dissimilarity of species composition among plots and sites.

The differences in sapling density between the control and mined sites may stem from the disturbance created by ASM. Several studies have already discussed how stand density is strongly affected by disturbances (Borah et al., 2014; Khamyong et al., 2003). Additionally, the removal of vegetation during mining may have compromised the growth and reproductive pattern of young species that may have transitioned into saplings (Borah et al., 2014). Moreover, depending on the magnitude of disturbance, seedlings of light-demanding species may not reach the sapling stage (Eilu and Obua, 2005).

5. Conclusion

Our study revealed that ASM methods affect species recruitment differently depending on the life stage of the species and the magnitude and extent of degradation. The mild degradation nature of the chamfi sites resulted in the rapid initial colonisation of some pioneer species. Stand characteristics showed that both ASM methods affected stand structure, with the effects on basal area and stand density being more pronounced when compared to their respective controls. Our research

Table 4. Sapling contribution (based on SIMPER) to the dissimilarity between sites A) chamfi main (CM) and chamfi control (CC) and B) alluvial main (AM) and alluvial control (AC) plots. (Av. Ab. = Average abundance, Contr = contribution percentage, Cum = cumulative contribution).

A Species	CM Av.Ab.	CC Av.Ab.	Contr%	Cum Contr%	B Species	AM Av.Ab	AC Av.Ab.	Contr %	Cum Contr%
Musanga cercropioides	0.18	0.41	10.41	10.41	*Musanga cercropioides*	0.19	0.69	19.91	19.91
Baphia nitida	0.04	0.37	7.98	18.40	*Hymenostegia afzelii*	0.23	0.51	16.04	35.95
Dialium guineense	0.04	0.28	7.55	25.95	*Ceiba pentandra*	0.04	0.29	9.25	45.20
Nauclea diderrichii	0.13	0.25	6.72	32.66	*Lecaniodiscus cupanioides*	0.09	0.25	9.23	54.44
Ceiba pentandra	0.00	0.27	5.88	38.55					
Rinorea ilicifolia	0.13	0.24	5.55	44.10					
Antiaris toxicaria	0.04	0.23	5.51	49.61					
Tectona grandis	0.10	0.20	4.73	54.34					

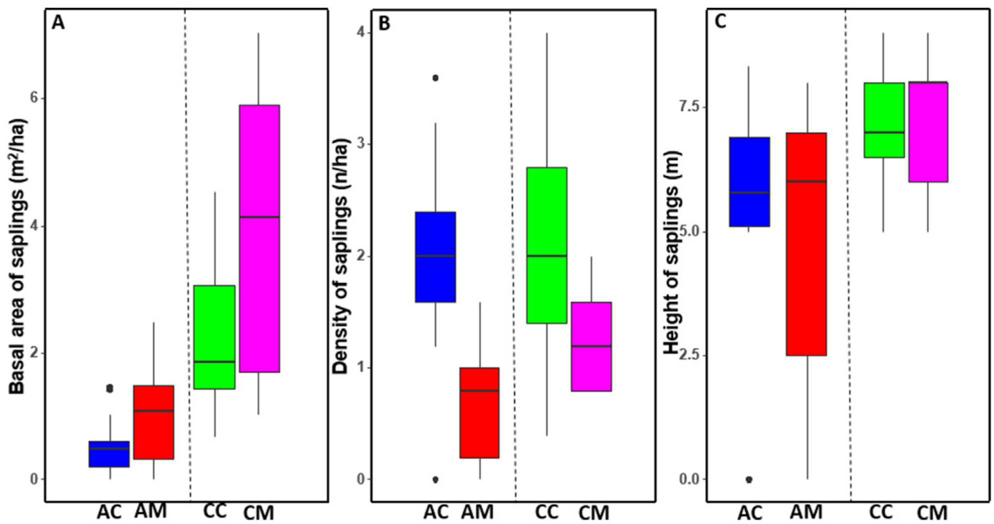

Figure 4. Box plots of A) sapling basal area, B) density of saplings and C) sapling mean height in the alluvial control (AC), alluvial main (AM), chamfi control (CC), and chamfi main (CM) plots. The line in the box represents the median value, and the box limits are the 25th and 75th percentiles. Error bars show the 10th and 90th percentiles on a log scale.

has helped to characterise the impacts of different abandoned ASM methods on the successional pattern of species. The study showcased that the chamfi method presented the best possibility of recovery, but the sapling composition showed that the alluvial method, albeit its higher magnitude of degradation exerted, seems realistic in its ability to recover some forest species. The lack of historical observation of the study site and absence of an intact primary forest as a reference site might have possibly underestimated or overestimated the differences between mined-out sites and their control and hence the impacts created by ASM. We recommend appropriate restoration and assisted regeneration remedies in mine areas irrespective of the method used where ecosystem resilience is limited.

Declarations

Author contribution statement

Desmond Asare: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Michael Ansong; Boateng Kyereh & Winston Adams Asante: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Frederick Gyasi Damptey: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Data availability statement

The data that support the findings of this study are openly available in figshare https://doi.org/10.6084/m9.figshare.16571172.v1.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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