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Early-stage restoration outcomes under active and passive rehabilitation interventions in a humid tropical forest

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Abstract

Restoration of degraded forests and landscapes is emerging as a global conservation priority. Opinion is divided, however, whether active restoration is a better approach than passive intervention in forest ecosystem rehabilitation. We assessed the variation in woody species composition and stand structure during the first five years of both active and passive restoration interventions in a degraded humid forest in western Kenya. Passive restoration entailed natural regeneration, while active restoration comprised planting at 5m, 1m and 0.3m spacing. The plots were protected from repeat incidences of disturbance using enclosures. Natural regeneration registered a significantly higher woody species richness (36.75±6.97) than active restoration (12.75±1.75). It had a higher Shannon-Wiener diversity index (3.05) than active restoration (2.32). Despite up to 10,000 seedlings per ha being planted under active restoration, woody stem density was significantly higher under natural regeneration (21,789±7,087 stems ha-1) than active restoration (13,118±1,857 stems ha-1). Mean sapling height was higher under natural regeneration (2.60±0.31 m) than active restoration (1.38±0.30 m). The results suggest that passive restoration interventions may be superior to active restoration approaches in rehabilitating degraded forest landscapes in the humid tropics if repeat incidences of disturbance are controlled. The long-held view that active restoration leads to greater woody species diversity and stand structure may have been spurred by the fact that ecological restoration interventions are often carried out in open sites that are exposed to continual incidences of disturbance, which tends to hamper the recruitment and survival of natural regrowth.

Keywords: Forest degradation; Early-stage restoration; Natural regeneration; Active restoration

1. Introduction

Forest and landscape restoration has emerged as one of the global priorities in the era of the climate change and biodiversity loss. It has a great potential to mitigate some of the emerging negative global impacts on mankind and ecosystem services [1, 2]. In this regard, the global community has come up with ambitious international commitments to restore at least 350 million ha of degraded lands by 2030 [3, 4]. Restoration efforts under this initiative appear to be bearing positive outcome, with the latest global forest resource assessment report indicating a 9.6% decline in the net rate of forest loss during the period 2010 – 2020 [5]. Despite an overall net global forest loss of 4.7 million ha per year during the period, Asia, Oceania and Europe recorded positive results [5, 6], while Africa and South America returned

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net losses [7, 8]. The results from Africa and South America suggest that the tropics could still be grappling with achieving a stable balance among sustainable natural resource offtake, selecting suitable restoration methods and dedicating adequate resources to landscape restoration efforts. Key drivers of vegetation loss in the tropics have been identified as weak controls in forestry sector governance, encroachment of subsistence agriculture into forest land, inadequate controls in resource offtake, poor choice of restoration techniques and low investment in forest restoration interventions [9, 10, 11].

The Global Forest Resources Assessment 2020 demonstrates that approximately ninety-three percent of global forests comprise naturally regenerated areas, while about seven percent (an equivalent of 290 million ha) accounts for planted forest [5]. The report identifies natural regeneration as a major source of forest restoration at the global level, and offers a window of opportunity for passive restoration as a primary landscape restoration intervention for resource-scarce continents, such as Africa, South America and Asia. Opinion is divided, however, whether passive restoration is a more effective forest restoration technique than active restoration [12, 13, 4].

It is generally agreed that both passive and active restoration techniques achieve good outcomes in regard to enhancing biodiversity status and ecosystem services [4, 14]. However, the two restoration techniques come with unique requirements and associated costs. Passive restoration is often considered less expensive, but it requires the protection of the restoration site from repeat incidences of disturbance, such as grazing, trampling, fires and wood harvesting [15, 16, 17, 18]. It also tends to thrive in sites of less severe disturbance, which in most cases retain potential sources of natural regrowth, such as remnant trees, live tree stumps, a rich soil seed bank and remnant forest stands in the vicinity [19, 12, 18]. The success of passive restoration tends to diminish with increase in the severity of site degradation, which in most cases leads to loss of potential sources of natural recovery [12, 1, 20]. Active restoration, on the other hand, often requires relatively more financial and operational resources to support the sourcing of tree seeds and consumables for a tree nursery, tree seedling production, managing the seedlings until they attain suitable planting size, transporting the seedlings to the planting site, and planting and maintenance of the restoration site until the planted seedlings can survive on their own [4, 6]. Given the many stages and processes involved, active restoration tends to cost relatively more than passive restoration. Nonetheless, most people still prefer it to natural regeneration [1, 5].

Despite a general preference for active restoration by forest managers, few studies have conducted a side-by-side comparison of the two restoration techniques [13, 4, 6]. The few studies conducted have shown contradicting results. Some have reported higher plant diversity for active restoration [e.g., 13], while others have reported similar plant diversity for both passive and active restoration interventions [e.g., 17]. In this paper, we assessed the variation in woody species composition and stand structure during the first five years of both active and passive restoration interventions in degradation hotspots in the Kakamega-Nandi Forest Ecosystem in western Kenya. Findings of this study are expected to improve the understanding of the comparative advantages of both passive and active restoration in the rehabilitation of degraded forest lands. Further, they will act as a guide for restoration managers on how to invest limited resources in forest and landscape restoration initiatives.

2. Material and methods

2.1. Study area

The study was carried out in Kibiri in Vihiga County and Kobujoi in Nandi County between April 2018 and March 2023. The two sites fall within the Kakamega-Nandi Forest Ecosystem in western Kenya. The forest ecosystem is the easternmost block of the Guineo-Congolian rainforest [21, 18]. It is located 0° 10’ N & 0º 21’ N and 34º 47’ E & 34º 58’ E at 1,600 to 1,700 m above sea level [18]. The eastern portion of forest ecosystem, which is referred to as South Nandi Forest, is located in a transition zone between the rainforest and the tropical Afromontane forest [22, 23]. This transition zone is located 0º 00´ & 0º 15´N and 34º 45´& 35º 07´E [24] and rises to an elevation of 2,000 m above sea level [25]. The area experiences a hot and wet climate with a diurnal temperature range 19ºC to 25°C and an annual precipitation of 1,500 to 2,000 mm [26, 27].

The forest ecosystem is estimated to have over 986 species of plants, approximately 300 species of birds and about seven endemic primate species [28]. The rainforest vegetation comprises a disturbed primary forest, old-growth secondary forest, relatively younger secondary forest stands in different stages of recovery, commercial forest plantations and some open fields [25, 18]. Over 112 woody species have been recorded in the old-growth forest and these include *Antiaris toxicaria* Lesch. *Strombosia scheffleri* Engl., *Funtumia africana* (Benth.) Stapf, *Celtis gomphophylla* Baker, *Ficus exasperata* Vahl and *Croton megalocarpus* L. [29, 28]. The gradual increase in elevation from tropical rainforest to tropical afro-montane forest leads to a minor shift in plant species characteristics [23]. Some of the unique woody species that one encounters in the transition zone to the afro-montane forest include *Macaranga* *kilimandscharicum,* and *Tabernaemontana stapfiana,* [24]. The forest ecosystem is classified as an Important Bird Area with new birds species still being encountered over and above the 300 species recorded so far [23]. Approximately 300,000 people border the forest ecosystem and directly derive their sustenance from it [30]. Some of the resources that they obtain from the forest include pasture for livestock, fuel wood, construction materials, herbal medicine, fiber, and wild fruits and vegetables [21].

2.2. Study design

The study employed a split-plot experimental design. The main plot was site protection using enclosures. Sub-plots were the various tree espacements under active restoration. Site protection was intended to stimulate natural regeneration by eliminating repeat incidences of site disturbance and any form of external interference. It is important to note that the same enclosures also protected active restoration plots. The unprotected areas surrounding the restoration plots served as the control. Active restoration plots comprised three spacing treatments: 0.3 m, 1 m and 5 m spacing. Eleven woody species were planted in the active forest restoration plots. The species comprised light-demanding secondary succession pioneers, shade-tolerant intermediates and late-stage successional species. Thus, together with natural regeneration and the control, the study consisted of five treatments. Assessment was carried out as described by Kaigongi et al. [31] in a 20m by 10m main plot for woody species with a diameter at breast height (DBH) larger than 10 cm. Woody species with stem DBH less than 10 cm were assessed in 10m by 5m sub-plots. Seedlings and saplings less than 1.5m in height were assessed in 2m by 1m sub-plots. The sub-plots were nested in the left-hand corner of the main plot. The treatments were replicated three times in each of the two sites.

2.3. Data collection

Data collection targeted woody species. Data were collected on species names, stem diameter at breast height (DBH) and sapling height on an annual basis. Seedlings and saplings of less than 1.5 m in height were recorded by species and count of stems. Woody species that could not be identified by botanic names were recorded by local names and their specimens carried to the herbarium for confirmatory identification.

2.4. Data analysis

Data were entered in Microsoft Excel for processing and descriptive analysis of species richness, woody stem density, mean DBH, DBH size-class distribution and mean sapling height. The difference in woody species diversity between active and passive restoration was analyzed using the Shannon-Weiner diversity index [32, 18]. In-depth data analysis was conducted in Genstat statistical software version 21 to determine the significance of variations in woody species richness, stem density, DBH and sapling height using analysis of variance (ANOVA) at 5% significance level. Post-hoc tests were carried out to separate means using the Ryan–Einot–Gabriel–Welsch Multiple Range Test at 5% significance level [33].

3. Results

3.1. Floristic composition

3.1.1. Woody species richness

A total of 54 woody species from 29 families were recorded. These included eleven woody species that had been planted for active restoration of the degraded forest sites. The addition of 43 new woody species through natural forest regeneration led to a significant variation in woody species richness among the five restoration treatments ($F_{(1,4)}$ = 13.85; p < 0.001). Post hoc tests indicated that the variation was attributed to a significantly higher woody species richness in plots under passive restoration (Figure 1). Apart from the eleven planted species, woody species richness of active restoration plots did not increase much. It was therefore not significantly different from control plots.

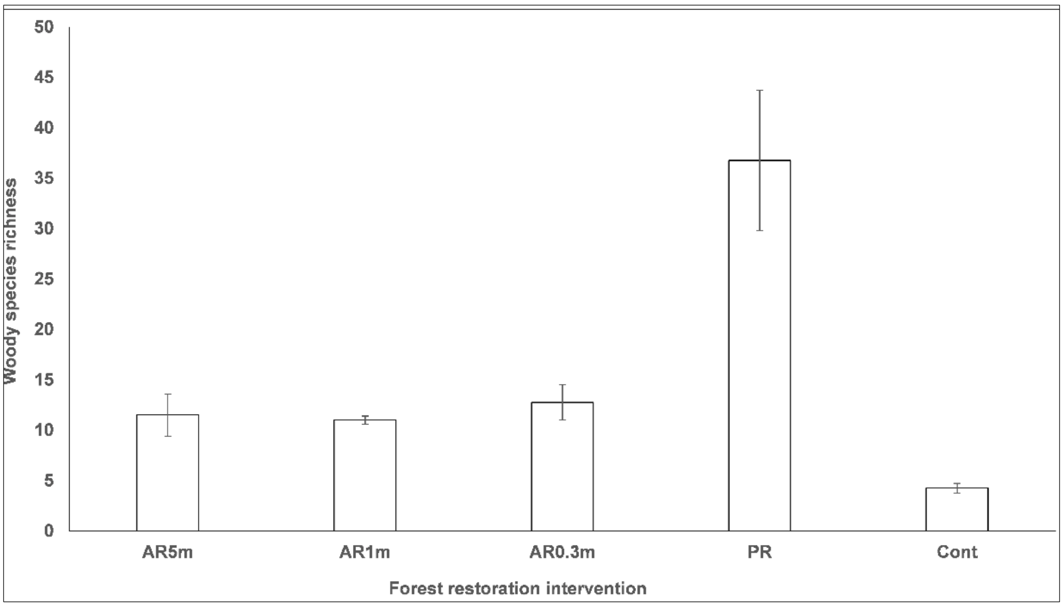

Figure 1 Variation in woody species richness in restoration plots in the Kakamega-Nandi Forest Ecosystem. AR5m = Active restoration at 5m spacing, AR1m = Active restoration at 1m spacing, AR0.3m = Active restoration at 0.3m spacing, PR = Passive restoration, and Cont = Control plot

3.1.2. Woody species diversity

The Shannon-Wiener diversity index for woody species diversity ranged between 1.13±0.01 and 3.05±0.72 (Table 1). Passive restoration plots had the highest Shannon-Wiener diversity index. Among, active restoration plots, 0.3m spacing had the highest Shannon-Wiener diversity index. Control plots had a relatively higher Shannon-Wiener diversity index than 5m and 1m active restoration plots.

Table 1 Woody species diversity in restoration plots in the Kakamega-Nandi Forest Ecosystem

Restoration intervention	Shannon-Wiener diversity index
Active restoration (5m spacing)	1.13±0.01
Active restoration (1m spacing)	1.67±0.45
Active restoration (0.3m spacing)	2.32±1.26
Passive restoration (unplanted, protected plots)	3.05±0.72
Control (unprotected, unplanted area)	1.77±0.42

3.2. Stand structure

3.2.1. Stem density

Stem density ranged between 396±29 and 21,789±7,087 at Year 5 (Table 2). The variation in stem density among the five restoration treatments was not statistically significant ($F_{(1,4)}$ = 1.60; p = 0.226). However, passive restoration registered a relatively higher stem density than active restoration.

Table 2 Stem density in restoration plots in the Kakamega-Nandi Forest Ecosystem

Restoration intervention	Stem density (stems per ha)
Active restoration (5m spacing)	396±29[a]
Active restoration (1m spacing)	2,450±1,523[a]
Active restoration (0.3m spacing)	13,118±1,857[a]
Passive restoration (unplanted, protected plots)	21,789±7,087[a]
Control (unprotected, unplanted area)	2,017±569[a]
	l.s.d. = 20,722.2 p = 0.226

3.2.2. Sapling height

Mean sapling height ranged between 0.50±0.18 m and 2.60±0.31 m (Table 3). The difference led to a significant variation in sapling height among the restoration treatments ($F_{(1,4)}$ = 7.76; p = 0.001). Post-hoc tests revealed that passive restoration and active restoration at 0.3 m spacing had significantly greater sapling heights than the other three treatments (Table 3).

Table 3 Mean sapling height in rehabilitated degradation hotspots in the Kakamega-Nandi Forest Ecosystem

Restoration intervention	Mean sapling height (m)
Active restoration (5m spacing)	1.32±0.29[ab]
Active restoration (1m spacing)	1.38±0.30[ab]
Active restoration (0.3m spacing)	2.54±0.46[b]
Passive restoration (unplanted, protected plots)	2.60±0.31[b]
Control (unprotected, unplanted area)	0.50±0.18[a]
	l.s.d. = 0.97 p = 0.001

*Different letters next to numerical results in the mean sapling height column denote significant difference of mean

3.3. Growth performance of woody species in active and passive restoration

Table 4 Comparing the growth performance of seven best performing woody species in active and passive restoration plots in the Kakamega-Nandi Forest Ecosystem. AR = active restoration, PR = passive restoration

Tree species	Mean tree height (m)		Mean tree DBH (cm)	
	AR	PR	AR	PR
Albizia gummifera	1.71	2.25	0.73	0.40
Croton macrostachyus	1.65	2.21	1.05	0.73
Croton megalocarpus	3.14	3.23	0.98	0.90
Harungana madagascriensis	2.90	3.77	1.56	1.60
Khaya anthotheca	2.17	2.00	0.60	0.50
Markhamia lutea	1.42	1.11	0.64	0.38
Spathodea campanulata	3.26	3.31	1.23	1.01

A comparison of the growth performance of the eleven tree species used for aided forest restoration indicated that *Harungana madagascariensis*, *Spathodea campanulata*, *Croton megalocarpus, Khaya anthotheca* and *Croton macrostachyus* were the fastest growing species. Being a light-demanding late successional pioneer, *Harungana madagascariensis* outperformed all the species in active restoration plots. The four woody species together with *Albizia* *gummifera* and *Markhamia lutea* also happened to have recruited naturally in passive restoration plots. A comparison of the seven species in active and passive restoration plots showed that they were relatively taller in passive restoration plots that in active restoration plots except for *Khaya anthotheca* and *Markhamia lutea* (Table 4). Despite being taller, all the species had relatively smaller stem DBH in passive restoration plots than the case in active restoration plots except for *Harungana madagascariensis*.

4. Discussion

4.1. Role of passive restoration in post-disturbance forest regrowth

The results of this study suggest that passive restoration performs better than active restoration in stimulating the recruitment and growth of native woody species. This is illustrated by the significantly higher woody species richness in passive restoration plots compared to the marginal increase in plots in all the three treatments under active restoration. The negligible number of woody species in the control area suggests that passive restoration is highly dependent on site protection from repeat incidences of site disturbance. Site protection is, however, not only critical to natural regeneration, it is important also for active restoration. The observation also tends to explain the long standing debate whether delay in post-disturbance forest regrowth is caused by site quality limitations or repeat incidences of disturbance, such as grazing, trampling, fire or cutting of saplings [1, 2]. The spontaneous increase in woody recruits, sapling height and stem diameter upon the erection of enclosures in sites that had been bare for over two decades gives an indication that the delay in post-disturbance forest recovery was likely caused by repeat incidences of disturbance rather than site quality limitations imposed by the initial disturbance. If the delay had been caused by site quality limitations, then site protection would not have had a spontaneous effect on natural forest regeneration. As noted by Zahawi et al. [12] and Flores & Holmgren [34], however, site protection may not lead to immediate natural forest recovery in a site that has lost natural sources of regeneration, such as live tree stumps, remnant trees that serve as seed sources, and a viable soil seed bank.

Despite illustrating the merits of site protection in forest restoration, it has a key limitation regarding the practicability of erecting enclosures over large areas because of the huge costs involved [12] and the likely ecological impacts on fauna [14]. In essence, forest managers could be more pragmatic in identifying viable local forest protection strategies that are both affordable and ecologically sound. In order to succeed, the protection strategies may have to address the underlying causes of forest degradation [9, 10]. For instance, in an effect to address uncontrolled grazing, grazing permits that are issued to livestock owners may have to clearly indicate the allowable livestock type, number of livestock permitted and areas available for grazing at any given time, as opposed to the current scenario where permit holders can have any number of livestock and graze their livestock in any part of a forest. Alternatively, livestock owners may be restricted to cutting grass in the forest and carrying it to their homesteads for their livestock. Such strategies would ensure that post-disturbance forest regrowth is not impeded by managerial decisions or lack thereof.

4.2. Passive or active restoration?

Although the Global Forest Assessment 2020 report [5] suggests that active restoration is presently favoured over passive restoration, the results of this study show that both forest restoration techniques have a role in regard to woody species establishment and growth performance in the humid tropics. The preference for any of the two restoration techniques should be guided by the rehabilitation needs of a given degraded forest site because they work best under different site conditions [2, 34]. For instance, passive restoration works better in degraded forest sites which are rich in sources of regeneration, such as remnant trees, a viable soil seed bank and / or stump sprouts, but it tends to be less effective in degraded sites where sources of regeneration have been removed through prolonged cultivation or repeat forest fires [16, 17]. Active restoration, on the other hand, works best in sites that have been exposed to relatively severe levels of forest degradation, which tend to lack potential sources of regeneration. It can also be applied to enhance woody species diversity in sites where forest degradation has significantly reduced tree species richness [35, 36]. However, it often presents a challenge of high cost of site establishment and maintenance of planted seedlings. The challenge becomes more pronounced if planting is carried out in a site with high potential for natural regeneration because planted seedlings end up being swamped by natural regrowth.

4.3. Selecting suitable spacing for active restoration

This study does not provide a conclusive finding on a spacing regime that can be considered most suitable under active restoration. The results suggest, however, that 5 m spacing does not provide an impressive outcome in the short term. The 0.3 m and 1 m spacing appear more promising, but they raise questions regarding the associated costs of establishment. A spacing of 5m may be more suitable for assisting natural regeneration to enrich woody species diversity, while 0.3 m and 1 m could be more relevant in sites where active restoration is the only intervention. It would be interesting to find out whether tree growth performance would vary significantly at 1.5 m, 2 m and 3 m spacing

5. Conclusion

Passive restoration appears to be a more viable forest restoration method than active restoration in landscapes rich in sources of natural regeneration, such as live tree stumps, remnant trees and a viable soil seed bank. It costs relatively less in terms of finances and operations and, tends to preserve a great deal of the original taxa at the restoration site. However, it only thrives under conditions of less severe degradation. Active restoration, though considered to be more costly, becomes inevitable under conditions of severe degradation where potential sources of natural regeneration have been lost and the site has shifted to an alternative stable state. The choice of woody species is an important consideration in active restoration because most of its sites tend to be open fields. Light-demanding, late successional woody pioneers tend to perform better in the initial stages than shade-tolerant species in active restoration. In this regard, at least 20% of the restoration species could be late successional pioneer species.

Compliance with ethical standards

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Author contributions

JO and SO designed the study. NL and JO participated in data collection. JO and SO analyzed the data. All the authors participated in manuscript preparation.

Disclosure of conflict of interest

All the authors declare that they have no conflict of interest.

Statement of ethical approval

The work presented in this manuscript dealt only with forest vegetation. It did not require ethical approval.

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