RESEARCH ARTICLE

Landscape Factors and Restoration Practices Associated with Initial Reforestation Success in Haiti

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ABSTRACT

Mountainous land in Haiti is highly degraded following decades of deforestation and erosion. Although mountainous landscapes represent an important target for forest recovery, there is a lack of empirical information to guide reforestation of sloping tropical lands. Using sapling survival data from 299 replicated reforestation plots planted with 24 dry forest species during 2007–2008 in Haiti, we examined the association of sapling survival with topographical, climatic, and landscape level variables. Our analysis indicates that the total number of surviving saplings was strongly correlated to sites with higher water availability, including sites with greater precipitation in dry months and sites with cooler (N/E) exposures. Sites with more adult remnant trees had higher sapling survival. Sapling survival was also improved by the use of best management practices of building micro-catchments and planting multiple sapling species into reforestation plots. Year effects were also significant and modified the effects of exposure, nurse trees, and soil rockiness. This temporal variation suggests sapling responses to environmental factors are sensitive to variation in rainfall.

Keywords: diversity, exposure, landscape ecology, mountain restoration, nurse tree, rainfall

Restoration Recap

- Haiti's deforested mountains provide a challenging environment for reforestation especially because of limited water retention and pronounced dry seasons which are aggravated by climate change (USAID 2016).
- Data from a reforestation project were analyzed to find the abiotic and biotic site characteristics associated with high sapling survival rates.
- The total number of surviving saplings was correlated to sites with higher water availability due to either higher precipitation or cooler exposures. A nurse tree effect of remnant trees was observed, as well as positive effects of planting diverse species of saplings and terracing techniques.
- The results varied depending on the year of planting, possibly tracking rainfall differences, and locality also had a very strong random effect.
- Although we expected negative effects on sapling survival from soil rockiness and steep slopes, they had no significant relationship with sapling establishment.

Deforestation and fragmentation of forests are causing the degradation of forest habitats globally. This can lead to shifts in the stable states of ecosystems from forest to savannah to degraded grassland (Hirota et al. 2011). This potentially irreversible loss of overall ecosystem productivity, vegetative structure, and soil fertility represents a form of desertification, which is common in subtropical climates of Latin America (United Nations Convention to Combat Desertification 2015). Desertification interacts with climate change to create even more difficult circumstances, especially increased drought stress, which have been particularly damaging in Haiti in recent years (Famine Early Warning Systems Network 2015). Deforestation-induced desertification, the risk of rising sea levels, and weak governance systems make Haiti one of the world's most vulnerable countries to climate change (Wheeler 2011). Reforestation has been promoted as a

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tool to reverse the process of desertification, particularly in China (Ma 2004, Moon and Park 2001, Cao et al. 2011, Ren et al. 2012). Before undertaking a reforestation campaign with limited resources in a desertified landscape, it is important to determine the principal environmental filters and limitations to planting success in order to choose the most effective methods and sites for reforestation. In this study, we took advantage of an ongoing reforestation effort to systematically test the effects on sapling survival of local microclimate, nurse trees, soil rockiness, and forestry practices including tree diversity and terracing.

Although steeply sloping lands compose the majority of the sub-optimal agricultural land available for reforestation in developing countries, particularly in Central America and the Caribbean (Aide et al. 2013), they are difficult to reforest. Steeply sloping lands are vulnerable to erosion and experience rapid surface runoff that limits soil water availability. A deforested mountainous landscape may shift to an alternative, degraded stable state (Veldman and Putz 2011, Carilla and Grau 2010) which may be particularly difficult to reverse in the face of changing global climatic patterns that change rainfall frequency and intensity (Hirota et al. 2011).

Haiti currently retains an estimated 1.4% mature forest cover (Grogg 2013), although the total tree cover in 2011, including fragmented vegetation and agricultural tree coverage, is estimated at 32% (Churches et al. 2014). In either case, this coverage is substantially lower than Haiti's estimated original 80% forest cover (Pierre 2001), and the process of deforestation spanned five centuries (Tarter et al. 2015). This massive decline in forest cover has not been reversed despite landscape restoration and management efforts from the international community for more than 50 years (Lundi 2012) because of non-sustainable approaches and a failure to address the underlying economic drivers of deforestation and degradation (Murray and Bannister 2004, Tarter et al. 2015). The Haitian Government launched a massive reforestation campaign in 2013 (Grogg 2013), but the campaign, as well as the relevant government entities needed to implement it, has been largely under-funded. Despite continued strong interest in reforestation, a good understanding of the combined social and ecological predictors of reforestation success is still largely lacking.

A major challenge to understanding factors affecting restoration success is that the importance of landscape-level predictors of species distributions may shift in a highly degraded landscape, and also may vary with topographically influenced microclimate elevation. Exposure relative to the equator strongly impacts the level of insolation received, especially on sloping lands, which in turn has been shown to impact water availability and the resulting plant communities (Rorison et al 1986). Sites facing away from the equator, and sites facing the east, receive less insolation and are generally cooler and wetter. Conversely, sites facing the equator, and the west, receive more insolation during the hottest part of the day (afternoon), and tend to be hotter and drier (Gelhausen et al. 2000).

Research on the recovery of abandoned agricultural land has revealed the importance of slope and surface stoniness in influencing vegetative succession (Benjamin et al. 2005). Although surface stoniness is often the result of tilling and erosion, especially on hillsides (Poesen et al. 1997), the stones themselves can sometimes serve as "rock mulches." Rock mulches have been shown to have multiple benefits not unlike nurse plants, including protecting exposed soil from irradiation/increased daily maximum temperatures (Perez 2009), reducing runoff and sediment yield (Guo et al. 2010) and increasing soil moisture retention (Perez 1998, Kaseke et al. 2012).

Another landscape factor that can influence the level of drought stress experienced by saplings is the presence of remnant trees that may provide a beneficial nurse-tree effect (Kinama et al. 2007, Sprenkle 2013). Nurse tree effects include improving the microclimate for growing saplings through increasing water availability (Stigter et al. 2002), providing shelter from wind desiccation, reducing heat load, suppressing competitive grass growth (Powers et al. 1997), and improving soil organic matter content (Forrester et al. 2006). Facilitation can also occur between saplings, particularly when multiple species are planted in mixtures, as more diverse plantations have been shown to improve ecological functioning of reforested areas, have higher stand productivity (Forrester et al. 2006), and greater resilience compared to monoculture (Plath et al. 2011, Griscom and Ashton 2011, Piotto 2008). Hence, the species richness of the planted saplings was considered as a factor that could impact the success of the plots.

Reforestation presents an opportunity for both ecosystem recovery and economic and agricultural development, however, creating agroforestry systems in completely deforested landscapes requires long timespans and significant economic and human investments. One potential approach is to work with local human populations as allies in designing reforestation projects that are both economically and socially beneficial to the community (Murray and Bannister 2004, Sprenkle 2008a, Locke 2013). The Haiti Timber Reintroduction Project (HTRIP) has been piloting this approach in Haiti since 2005 in association with Hôpital Albert Schweitzer Haiti in the Artibonite Valley. To support the overarching goals of improved resilience, increased food security, and stronger local economies, the project works with mountain communities to initiate reforestation activities to create sustainable forestry and agroforestry production. The Haiti Timber Reintroduction Project provides agroforestry education and minimally subsidizes soil conservation and tree planting efforts at the community level in a joint-venture approach where the participants do eventually expect to make a profit from forestry/agroforestry in the plots.

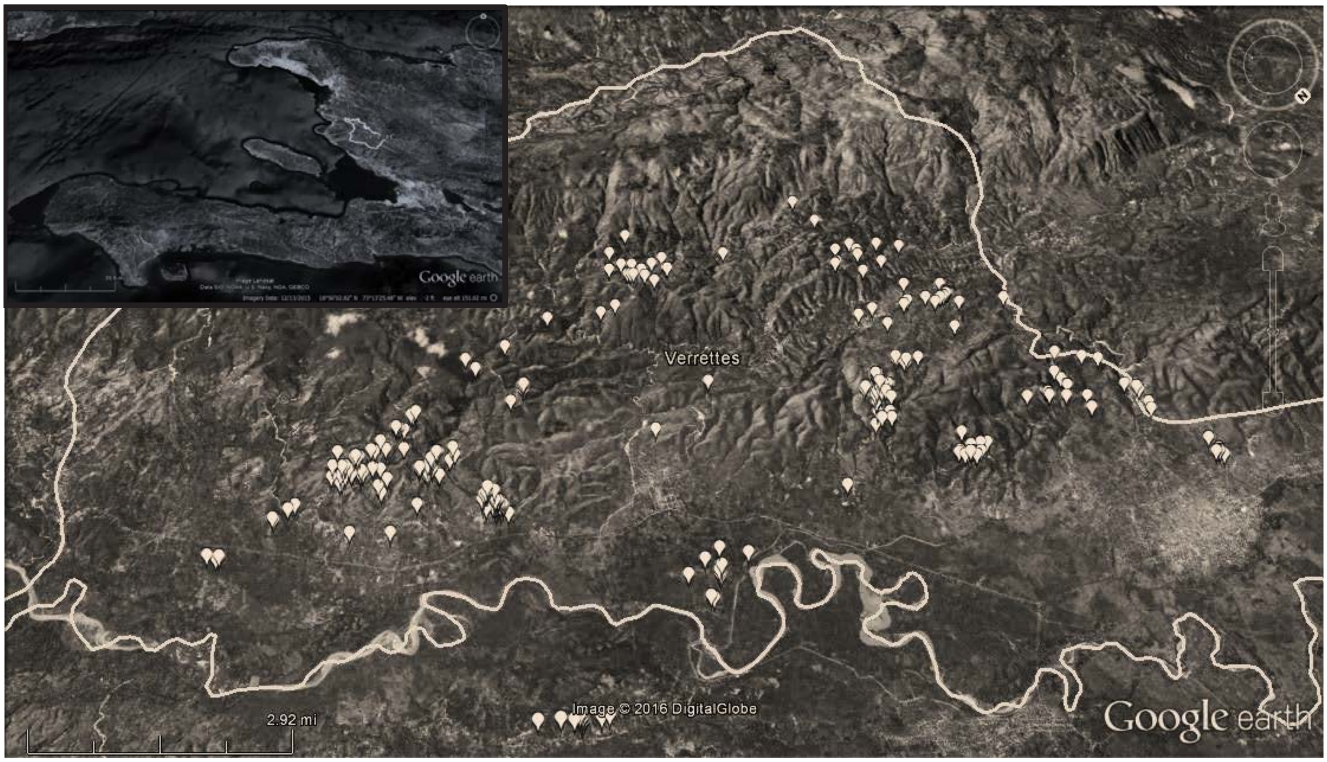

Figure 1. South-facing view of the reforestation plots in Verrettes, Artibonite Valley, Haiti (study area shown in inset) generated using Google Earth.

In this study, we studied survival of more than 30,000 saplings in 299 replicated reforestation plots to assess the importance of a range of factors for tree survival and growth (listed below) while also providing a scientific evaluation of the effectiveness of a major reforestation effort. Water is a survival-limiting resource on sloping land in seasonally dry subtropical regions such as the study area, as rapid runoff reduces infiltration, while high insolation and wind can create high rates of soil and plant water loss (Vallejo et al. 2012) leading to sapling mortality. We thus focused this study on environmental variables that are related to plant water availability and drought stress. We considered three general categories of variables:

1. Reforestation techniques. We examined whether soil conservation installations (i.e., terracing), considered as a "best practice" for hillside reforestation in Haiti but requiring significant labor to install, actually improve sapling establishment (hypothesized positive association).
2. Abiotic environmental factors. We predicted that landscape features such as greater slope and increasing soil rockiness (as a proxy indicator of the level of erosion at the site) would negatively affect sapling establishment. In contrast, we predicted that cooler northern and eastern exposures, as well as higher elevations, would be associated with greater sapling establishment. In terms of climatic factors, we expected that lower precipitation and warmer temperatures would be associated with lower rates of sapling establishment.
3. Biotic factors. We predicted that increased species richness of the planted saplings and the presence of remnant "nurse" trees would be correlated with greater sapling establishment.

Methods

Study Area

The study sites are located within a 400 km^2 area, primarily on the southern side of Haiti's Artibonite Valley, in the Matheaux mountain chain; some sites are on the valley floor and a few extend into the opposing Caheaux Range (19°03′ N; 72°30′ W, Figure 1). The soils are lithic calciustolls of Eocene limestone origin (Draper et al. 1995) with high calcium levels and low levels of other soil nutrients including Phosphorous (soil analysis by Pennsylvania Cooperative Extension). The A horizon is very shallow, rarely greater than 10 cm deep, and one can often observe exposed B and C horizons (S. Sprenkle-Hyppolite, personal observation). Typical for eroded sites, the soils have high dry bulk densities indicating mineral composition with a very low organic matter fraction (average dry bulk density of 1.4 g/cm^3 across a sampling of 6 sites in 6 different localities from Sprenkle 2013).

Rainfall in the region averages 1300 mm/year, with a range of 977–1602 mm/year for the study sites (Hijmans et al. 2005). Rainfall is strongly seasonal, with an early rainy season in April–June followed by a brief dry period, and then rainfall during the hurricane season from August–December followed by a major dry period from January to April (Ehrlich et al. 1986, ORE 2013). It is important to note that the study region is inland in Haiti and experiences very little differentiation of precipitation based on exposure, compared to the northern and southern mountain ranges which show trends of increased precipitation due to coastal exposure and elevation. Mountain ranges to the north and south create both a strong rain shadow and protection from hurricane-force winds. The slopes are irregular and highly dissected by ridges and ravines so that the microtopography varies greatly, leading to a variety of exposures at the plot level that and likely influence microclimate variation across strong contrasts in insolation level. The mean temperature is 25°C (site range 21–26°C), with maxima of approximately 34°C at sea level (Hijmans et al. 2005).

Like most low to mid-elevation regions of Haiti, this area was once covered with tropical dry forest (Holdridge 1945, Earth Institute 2012) but has undergone successive episodes of deforestation starting in the 1600s and intensifying in the 1900s (Pierre 2001, Tarter et al. 2015). The Artibonite Valley is one of the more recently deforested regions of Haiti as it had 17% cover still remaining in 1986; well above the national average (Ehrlich 1986). The study area is similar to other parts of the country in that rates of soil erosion are extremely high because of steep slopes, extensive deforestation, intensive cultivation, and intense rainfall events (Ehrlich et al. 1986, Paskett and Philoctete 1990, Williams 2011). The land use matrix in the mountainous study area is dominated by annual cultivation (field corn, millet, and bush bean) and grazing land characterized by very sparse tree cover, as well as home gardens that include some tree cover. Reforestation plots were located in all three of these land use types, with the majority in the annual cultivation/grazing land type, hence, plots were very sparsely vegetated at the time of tree planting. A fourth land use type, hanging valleys with access to irrigation supporting a larger variety of crops and fruit trees, was very rarely chosen for reforestation.

Planting and Census Methods

In the HTRIP project, cohorts of 20–30 community members receive training each year and establish small (< 1,000 m^2) reforestation plots of 100–200 trees on their properties. As of 2015, the program has reached 63 communities and has planted over two million trees. This project has resulted in the establishment of thousands of small (average area 286 m^2) reforestation plots planted with multiple species. Twenty-four native and naturalized tree species in total were planted during the study period (see species list in Supplementary Table 1), with a maximum of 10 species per plot and a mean of 3.4 species per plot. The majority (17/24) of the species planted are fast-growing, drought-adapted "pioneer" type timber species appropriate to the climate and soil conditions. Five leguminous species, among them four timber species, were used to enhance soil quality, and six varieties of fruit trees were tested (see tree "type" in Supplementary Table 1). For this study, HTRIP managers created a database to examine the plot-level factors that predict tree survival and growth, to gather information to guide future site and species selection.

The implementation of the project was highly dependent on the participation of the local community leaders (Sprenkle 2008b). Local leaders were volunteers, regularly trained by the program, and acted under light supervision from project staff due to transportation and time constraints. Plots were prepared with terraced micro-catchments at 3 m intervals along slope contours to reduce runoff and erosion. Within an annual planting cycle, saplings were started from locally collected seeds and grown for three months (March–May) in small plastic bags in nurseries and planted out from June to September. This pattern allows for establishment during the rainy season, since supplemental watering is not feasible for the practitioners who don't have access to irrigation. Planting holes were approximately 0.3 m wide and 0.5 m deep and the equivalent of a dry liter volume of locally produced manure-based compost was placed in each hole before planting the tree to enrich the otherwise rocky, leached substrate. On average, 100 saplings of multiple (average of 3) species were planted in each plot, with ~2 m spacing. The actual number and types of saplings depended on the production levels of the local community nursery. The HTRIP methods are covered in greater detail in Sprenkle (2008a).

For this study, each plot of saplings was treated as an experimental unit. Of a total of 299 plots surveyed in a comprehensive survey covering every plot established in those years, 125 were planted in 2007 and 174 in 2008 with a total of more than 30,000 saplings planted across 17 localities/communities. Between November 2009 and March 2010, all of these plantings were monitored once for sapling survival; the numbers surviving at the time of the survey are given in Supplementary Table 1. This census captured the most important mortality window for all planting years because most sapling mortality occurs in the first year due to transplant shock or exposure to drought (Sprenkle 2013). During the census we also recorded plot location, the total linear meters of micro-catchments installed in the plot, as well as plot slope and slope aspect. The rockiness of the plot was quantified as the percent of the soil cover composed of rocks using three 0.5 m × 0.5 m squares divided into four quadrants. The number of adult remnant trees already within the plot was also recorded. The expected range of nurse effects, up to a 30 m radius per Sprenkle 2013, was greater than the average plot diameter, so all remnant trees in the plots were considered potential "nurse" trees. We used the latitude and longitude for each

Table 1. Plot characteristics from 299 small dry forest reforestation plots in Verrettes, Artibonite, Haiti, tested as explanatory variables in the regression model to predict sapling survival, with the author's predicted associations.

Variable Name	Type	Description	Range	Mean	Predicted Association
Elevation	numeric	in meters, extracted using latitude and longitude coordinates (GPS Visualizer- Schneider 2014)	32–664	281	+
Rockiness	numeric	percent of soil surface that is covered in rocks- an indicator of soil disturbance, cultivation, and erosion	2–60	21	–
Mean precipitation (precip)	numeric	average monthly precipitation in mm (WorldClim- Hijmans et al. 2005)	977–1494	1277	+
Mean temperature (temp)	numeric	average monthly mean temperature in °C*10 (WorldClim-Hijmans et al. 2005)	226–264	252	–
Max temp	numeric	average monthly maximum temperature in °C*10 (WorldClim-Hijmans et al. 2005)	294–333	321	–
Precip driest	numeric	average monthly precipitation for the driest month in mm (WorldClim- Hijmans et al. 2005)	33–79	46	+
Remnant trees	numeric	number of remnant "nurse" trees in the plot including along the edges of the plot	0–67	6	+
Shannon biodiversity	numeric	index that integrates species richness and species evenness for the saplings in the plot: $\Sigma \log_{10} (n_{\text{individuals of species } i}/n_{\text{total individuals}})$, multiplied by –1 to make it positive	0–1	0.41	+
Microcatchments	numeric	linear meters of terracing micro-catchments installed in plot	0–576	95	+
Slope	numeric	steepness of slope in percent (100% = 45°)	0–45	16	–
Exposure	categorical	the direction that the slope is facing (aspect) was recorded in the field, then aspects were regrouped into "cooler" and "warmer" exposures. Cooler: E, N, NW, and NE. Warmer: W, SW, S, SE.	Number of plots: 182 "cooler" 99 "warmer"		Cool = + Warm = –
Year Planted	categorical	year saplings planted (number of plots)	2007 (125), 2008 (174)		n/a
Locality	random	the geographically defined human community within which the plot is located	17		n/a

plot to obtain its elevation using GPS Visualizer™ (Schneider 2013), and to extract mean precipitation, precipitation in the driest month, mean temperature, and max temperature from the WorldClim global climate layers (Hijmans et al. 2005).

Data Analysis

The explanatory landscape variables that we selected and their value ranges are described in Table 1. We partitioned the data using year of planting as a fixed effect to examine year and age effects. We included a quadratic term for precipitation with an expectation that there would be a diminishing return in the effect of increasing precipitation on sapling survival. All numeric predictor variables were standardized, centered and scaled (i.e., converted to z-scores) before analysis to facilitate comparison of regression coefficients. Slope aspects were grouped into "cooler" and "warmer" exposure classes. Given that the site is in the Northern Hemisphere, we included northern and eastern slope aspects in the "cooler" exposure class while western and southern slope aspects were grouped into the "warmer" exposure class.

In order to limit the number of variables in the model, we examined variable cross-correlations. Cross-correlations among most non-climate-related explanatory variables were low, with four out of ten cross-correlations having Pearson correlation (r) values less than 0.18 (Table 2). All variables with relatively low intercorrelations ($r < 0.5$) were included in the model. Although temperature and precipitation variables were highly correlated with each other, and with elevation (r ranged from 0.7–0.9, Table 2), we still felt it was important to include climatic indices of both precipitation and temperature. We decided to retain precipitation of the driest month and maximum temperature of the warmest month since these are likely the best indicators of water limitation during dry seasons, when we expect the saplings to experience maximal environmental stress.

Data on the number of saplings planted were not available for all sites, so we assumed that all of the plots started out with approximately the same number of trees, and used the total remaining saplings as a Poisson-distributed proxy for survival in the plots. We based this assumption on the fact that the project's protocols dictated that each participating community should receive 100 saplings per participant that were then distributed evenly among the community members planting saplings that year. The existing detailed planting records indicate that this planting target was generally achieved, with an average and median

Table 2. Pearson's cross-correlations r values between continuous variables describing reforestation plot characteristics; asterisks (*) denote variables that were eliminated due to high level of cross-correlation.

	Elevation*	Rockiness	Shannon	Slope	Nurse Trees	Mean Precip*	Mean Temp*	Driest Precip	Max Temp
Elevation*									
Rockiness	0.233								
Shannon	–0.118	–0.059							
Slope	0.465	0.115	–0.097						
Nurse Trees	–0.148	–0.095	–0.049	–0.076					
Mean Precip*	0.553	–0.047	–0.090	0.381	–0.052				
Mean Temp*	–0.762	–0.163	0.028	–0.347	0.129	–0.611			
Driest Precip	0.696	0.032	–0.040	0.378	–0.017	0.796	–0.828		
Max Temp	–0.739	–0.183	0.012	–0.318	0.136	–0.515	0.990	–0.758	
Microcatch-ments	–0.172	–0.055	–0.092	–0.019	0.085	0.093	0.132	0.022	0.165

planting total of 95 trees per plot. We also assumed that the final level of sapling species richness in the plot remained proportionate to the original level of planted diversity. We analyzed the data using a Poisson generalized linear mixed model in SPSS (IBM SPSS Statistics Version 20) with the locality (human "community") as a random effect and year of planting as a fixed effect. We looked for possible interactions between all of the explanatory variables, but then refined the model by removing non-significant interactions. The selected final model had the lowest Akaike Information Criterion (AIC).

Results

The overall model used only 221 of the 299 plots due to missing data, and exhibited a good fit as seen in Figure 2 ($F = 48.0$, $p < 0.001$). "Community"/locality was a highly significant random effect (z-score 2.49, $p = 0.013$). Planting year was a significant fixed factor (coefficient = 0.684, Table 3), with an estimated mean of 63.6 surviving saplings from the 2007 cohort versus only 41.2 from the 2008 cohort. Other significant environmental factors in the model included mean maximum temperature (coefficient = 0.445) and elevation (coefficient = –0.173), see Table 3, indicating higher numbers of surviving saplings at higher temperatures and lower elevations. The simple effects of rockiness and slope were not significant.

Exposure and precipitation in the driest month (linear component) had the largest absolute magnitudes of coefficients, and these two factors also had a significant interaction (coefficients –1.784 and 0.148, Table 4). The coefficient value (effect size) of cooler exposures was 5.4 ($p < 0.001$, Table 3), indicating that, as predicted, cooler exposures had higher numbers of surviving saplings than warmer exposures. This pattern was strong in the overall model, but also had a significant interaction with the planting year. In 2007, a particularly wet year (ORE 2013), the trend reversed, with warmer exposures exhibiting higher surviving saplings (interaction coefficient –0.4, Table 4). Precipitation in the driest month had the second most important effect size, and was a positive association as predicted (coefficient

Table 3. Fixed effects of the final model describing the impact of plot characteristics on total surviving saplings in dry forest reforestation plots, Verrettes, Artibonite, Haiti. Separate *p* values are shown for F statistics and coefficients.

Fixed Effect	F	*p*	Coefficient	*p*
Exposure	28.1	< 0.001	5.396	< 0.001
Driest Precip^{linear}	53.9	< 0.001	3.334	< 0.001
Year	210.6	< 0.001	0.684	< 0.001
Max Temp	46.4	< 0.001	0.445	< 0.001
Driest Precip^{quadratic}	45.1	< 0.001	–0.223	< 0.001
Nurse Trees	204.2	< 0.001	0.195	< 0.001
Elevation	12.1	0.001	–0.173	0.001
Shannon biodiversity	127.8	< 0.001	0.132	< 0.001
Microcatchments	17.6	< 0.001	0.096	0.001
Rockiness	0.002	0.967	–0.046	0.004
Slope	2.9	0.092	0.028	0.092

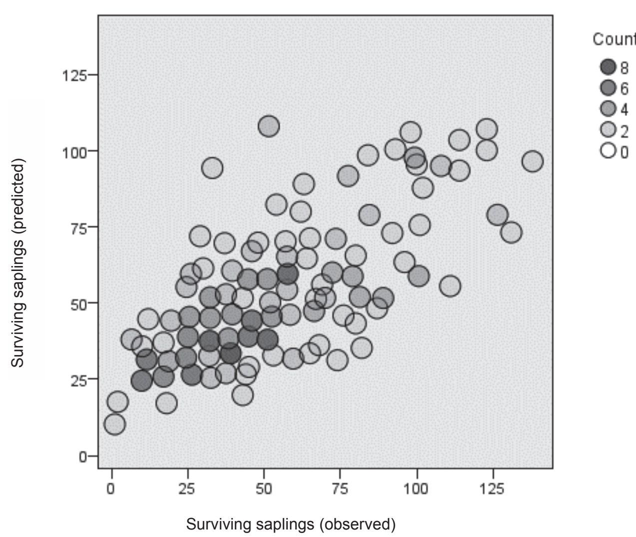

Figure 2. Overall fit of the model predicting total surviving saplings from plot characteristics of the reforestation plots in Verrettes, Artibonite Valley, Haiti.

Table 4. Significant year and exposure interactions with other fixed effects showing the interaction of plot characteristics on total surviving saplings in dry forest reforestation plots, Verrettes, Artibonite, Haiti. Separate *p* values are shown for F statistics and coefficients. *Coefficients were calculated using 2007 as the baseline for year and northern exposures as the baseline for exposure.

Year Interaction	F	*p*	Coefficient*	*p*
Year2007 × Nurse Trees	18.6	< 0.001	–0.087	< 0.001
Exposure Interactions				
ExposureN × Precip^{linear}	31.7	< 0.001	–1.784	< 0.001
ExposureN × Year2007	53.3	< 0.001	–0.385	< 0.001
ExposureN × Precip^{quadratic}	34.9	< 0.001	0.148	< 0.001
ExposureN × Microcatchments	5	0.027	–0.064	0.027

3.3, Table 3). To further explore the effect of precipitation, we combined the linear and quadratic coefficients for precipitation in the driest month into a single line plotted against precipitation in the driest month relativized to its standard deviation (Figure 3). There was a strong positive response to precipitation in the driest month, although this effect was nonlinear and reached a relative plateau at about 60 mm (i.e., ~30% above the mean). Cooler exposures interacted with precipitation (coefficient = –0.784) and precipitation^2 (coefficient = 0.148) showing no saturation at any level of precipitation; this response is also shown in Figure 3.

Biotic factors, including the species richness of saplings in the plot (i.e., Shannon diversity index, coefficient = 0.132, $p < 0.001$) and association with remnant "nurse" trees (coefficient = 0.195, $p < 0.001$) were positively associated with sapling survival (Figure 4). There was a significant interaction between planting year and number of nurse trees (coefficient = –0.087, $p < 0.001$, Table 4), because of a less pronounced positive response to nurse trees in the 2007 cohort when compared to 2008.

The micro-catchment technique had a small but still significant positive association (coefficient = 0.096, p = 0.001), and micro-catchments showed an interaction with exposure (coefficient –0.064) such that they had more of a positive impact on survival on warmer exposures.

Discussion

The main drivers of reforestation success (sapling survival) in this study were related to local water availability, which is not surprising considering that the plots are located in a climate with strong seasonal drought, and sapling survival was dependent on rainfall (non-irrigated). Sensitivity of survival to water availability is supported in multiple effects in the model. Northern and eastern exposures, typically

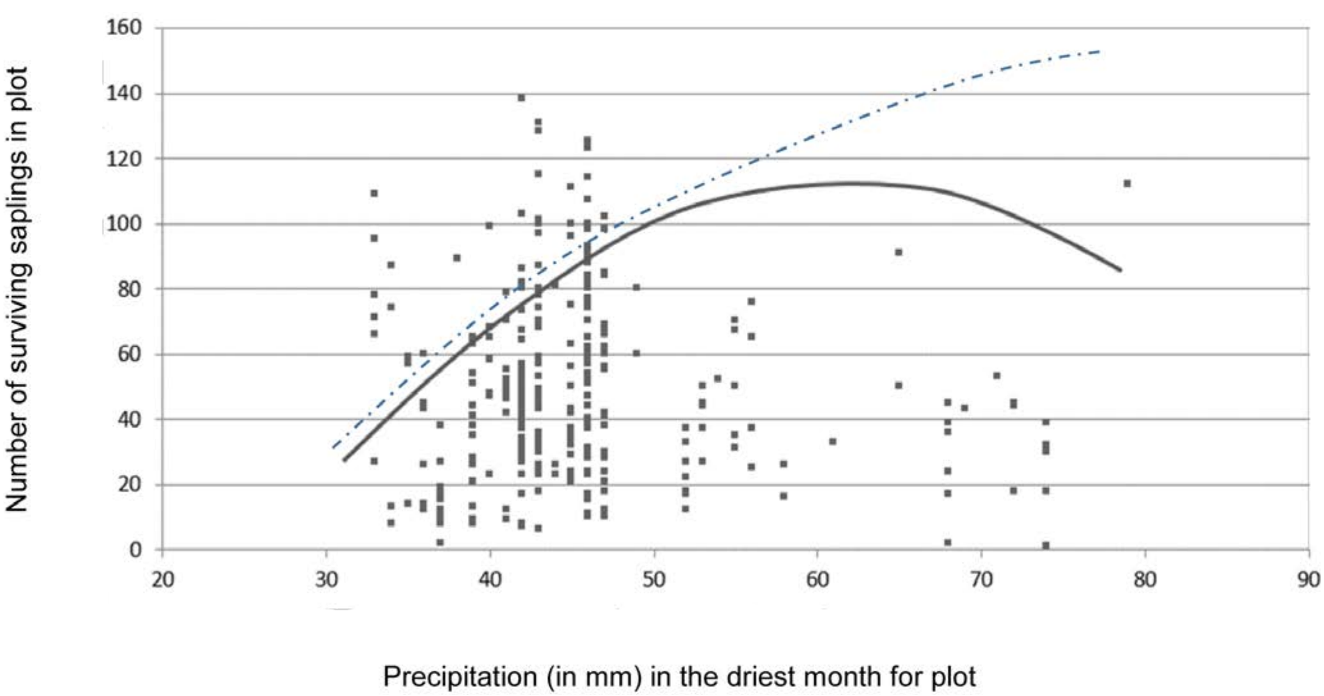

Figure 3. Survival response of dry forest saplings to precipitation in driest month: non-corrected raw data points overlayed with combined linear and quadratic function across all sites (solid line) and in cooler exposures (dashed line).

cooler and wetter in the Northern Hemisphere (Pope and Lloyd 1975), were associated with higher numbers of surviving saplings in the drier year of 2008, though not during the wetter year of 2007, suggesting that the threshold value of precipitation necessary to mitigate the effects of a warmer slope may be reached some years and not others following annual rainfall variation. We would expect exposure to influence sapling survival generally in Haiti, although the strength of the effect would be reduced at wetter, higher elevations in coastal-facing mountains. Other evidence for the importance of water availability was provided by results that indicate increased precipitation in the driest month was beneficial for sites that had below-average precipitation (Figure 3)

Higher temperatures (coefficient 5.4) and lower elevations (coefficient –0.173) were significantly associated with greater sapling survival, contrary to our original hypothesis. This suggests that the species planted were adapted lower elevations with their corresponding higher temperatures, and that the suite of species would need to be adjusted to increase planting success at higher-elevation sites (elevation > 500 m). For future projects, climate data available online (Hijmans et al. 2005) could be used to allow practitioners to predict where the drier/wetter and warmer/cooler local climates will be within a landscape, and then choose species with varying degrees of drought tolerance for the appropriate areas. The timing of sapling out-planting with regards to the seasonal rainfall patterns within a year could also be very important for survival, as shown in other climates (Richardson-Calfee and Harris 2005, Li et al. 2014). In general, HTRIP times sapling out-planting to the beginning of the consistent rains, to maximize the chance for successful establishment during the rainy season, although the ideal time window is difficult to identify, and changes annually. The current dataset does not have the specificity to permit an analysis of time of planting with regards to intra-seasonal rainfall patterns, although the topic merits further investigation. Supplemental watering in the dry season might be considered to ensure sapling survival in drier sites or in dry periods within the establishment season, but the thresholds of minimum rainfall levels at which supplemental watering would become necessary, and the cost-benefit tradeoff of watering, need to be investigated further.

Surprisingly, neither steepness nor the rockiness of the soil significantly affected sapling survival. Rockiness may indeed be both an indicator of erosion but may also provide benefits in terms of "rock mulching" soil moisture retention; further study is required on rock mulching as a factor promoting sapling establishment. At this point, our results suggest that sloping and rocky terrain might provide viable reforestation sites, especially if the other microclimate factors discussed above indicate favorable site conditions. This is heartening for the case of Haiti, considering it is extremely mountainous, highly eroded, and appears to be an improbable area for reforestation success.

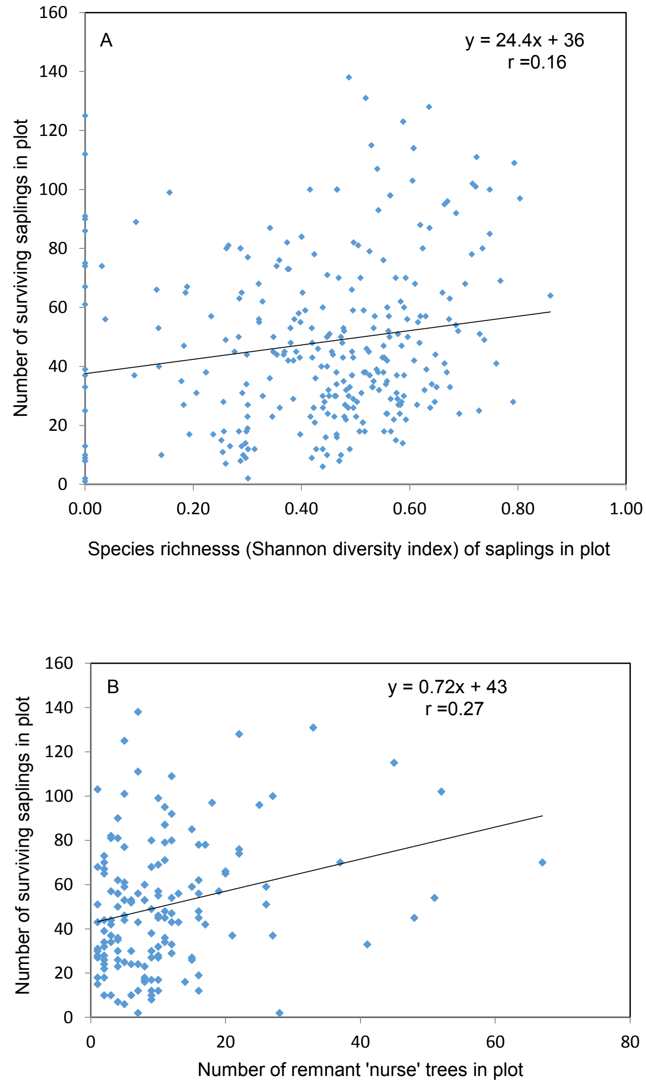

Figure 4. Bivariate correlations between dry forest sapling survival and the plot characteristics of A) species richness and B) nurse trees.

In addition to abiotic factors, reforestation techniques were also important contributors to sapling survival. The results support the best practices planting reforestation plots with a diverse mix of sapling species, with survivorship increasing in plots with a Shannon biodiversity index greater than 0.40 (coefficient 0.132, Table 3), and of building micro-catchments (coefficient 0.096, Table 3), particularly in warmer/drier southern and western exposures (coefficient –0.064, Table 4). Our results also suggest a strategy of associating reforestation plantings with remnant "nurse" trees to increase sapling survival (coefficient 0.195, Table 3), as increased numbers of remnant trees in plots were positively associated with increased survival. This "nurse" effect of solitary remnant trees is associated with increased performance of saplings up to 30 m away and may be expected to be stronger when multiple nurse trees are present (Sprenkle 2013), due to either abiotic microclimate amelioration and/or nutrient enrichment by the nurse trees (Gomez-Aparicio et al. 2004, Duarte et al. 2010, Becerra and Montenegro 2013). The interaction between the "nurse" effect and planting year (coefficient –0.087, Table 4) showed that higher numbers of remnant trees per plot had a bigger positive impact on survival in the drier year (2008), which is consistent with ecological theory indicating that facilitation of plant establishment by nurse plants tends to be stronger under more stressful conditions (Bertness and Callaway 1994, Callaway and Walker 1997, Castro 2002) and suggests an increasing importance of remnant "nurse" trees under climate change scenarios.

Although the "planting year" variable (coefficient 0.685, Tale 3) confounds the effects of planting year and sapling age because 2007 saplings were one year older at the time of data collection, we would still argue that planting year effects (Vaughn and Young 2010), rather than age effects, are likely to be more important drivers of the observed survival patterns. First, the number of surviving saplings was much higher for the 2007 cohort than the 2008 cohort, even though the trees were older at the time of sampling and, of course, all things being equal we would expect higher mortality after a longer time. Considering that the same methods were used in both years, the overall greater survival for the 2007 cohort may reflect the higher rainfall in 2007 (ORE 2013) that may have increased the initial rate of establishment. The importance of conditions during the planting year is also indicated by the significant year by exposure interaction (coefficient –0.386, Table 4), where higher rainfall in 2007 enabled more saplings to establish in the warmer exposures, compared to the drier year of 2008 where cooler exposures exhibited higher survival. HTRIP managers have observed that the critical time period for sapling establishment is the first dry season, with lower additional mortality rates in subsequent years (Sprenkle 2013).

More generally, our results highlight that reforestation outcomes may be highly contingent on the year in which they were carried out. This has implications for both restoration research and restoration practitioners (Vaughn and Young 2010). Restoration experiments carried out in a single year run the risk of interpreting treatment effects as general, when they may be particular to that experimental year. Restoration practitioners, not to mention farmers, have long recognized that planting success can differ from year to year, and could use better direction from researchers on how to more efficiently plan for such inter-annual variation. The random effect of "community"/locality explained a large amount (48%) of the variation in the overall model. Besides covering unmeasured environmental differences that vary by at this spatial scale (see Figure 1 for the extent of a typical "community"), this variable may also reflect socioeconomic differences elevation among communities, such as poverty levels (Sprenkle 2008b).

Though our final model includes sixteen significant effects, we know that we have not captured all of the contributing factors that determine the total surviving saplings in each plot. A number of factors could contribute to the unexplained variation in the model. Notably, the level of interest, capacity to learn and teach, and public relations skills of the local community leaders varied greatly and could have influenced plot success at the locality/community level. Because communities are defined by geographic areas, there is also a certain level of co-variation of other landscape variables with human community factors.

The strong interconnection between this research and the HTRIP project underline the importance of rigorous monitoring and evaluation in paired reforestation and development projects. Considering the massive variation in sapling responses across the plots, a comprehensive dataset of hundreds of sites was required to support this multivariate analysis and lead to useful insights on landscape and technical factors influencing reforestation success. Building the data collection systematically into the project resulted not only in the creation of a useful database that now contains thousands of sites, but also in significantly increasing the technical and analytical capacity of the local staff, which assured the success of this study and could be further capitalized on with related investigations. Further investigation could, for example, explore potential socioeconomic factors associated with "locality" that may help explain more of the variation in reforestation success among local administrative units.

Conclusion

These results indicate that the abiotic conditions, mostly related to water availability, have strong correlations with sapling survival in this dry forest system. This suggests that desertification and land degradation may further reduce the availability of establishment sites for typical dry forest species. The situation is likely to become even more challenging in the face of global climate change, which is increasing the frequency of drought in many tropical areas. Climate change may not only reduce the frequency of good rainfall years but also make them more difficult to predict, thus reducing the likelihood that practitioners will be able to anticipate good rainfall years for large-scale plantings.

Even with a reduced ability to predict good rainfall years, our results suggest that reforestation success rates can be increased by targeting more mesic microclimates and exposures for planting sites, and by using reforestation best practices such as using micro-catchments and diverse plantings, and associating plantings with existing nurse trees where possible. While the processes underlying nurse tree facilitation of sapling survival need further study, our results suggest strategically planting saplings with existing trees in dry forest landscapes. The multivariate approach means that we were not able to extract definitive thresholds for individual variables, however, our data suggests that planting saplings on warm exposures with low precipitation rates in the dry months will have limited success, even with the application of terracing and association with nurse trees.

The deforestation trend in Haiti may finally be reversing. Aide et al. (2013) detected a small net gain in forest cover of 151 km^2 in Haiti from 2000–2010, representing 0.6% of the country's land area. The Landsat analysis done by Churches et al. (2014) shows that the HTRIP project area has a higher density of tree cover than surrounding areas. Yet, with the majority of the country still without tree cover, it will be important to continue to plan reforestation with rigorous technical and quality control and strong, ecologically-based monitoring and evaluation. In this way we will maximize learning and continue refining techniques for designing the most efficient, cost-effective interventions.

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