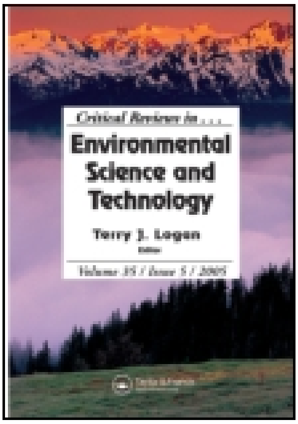

Critical Reviews in Environmental Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/best20

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Available online: 19 Feb 2011

To cite this article: Craig S. Smith, Lauren Serra, Yuncong Li, Patrick Inglett & Kanika Inglett (2011): Restoration of Disturbed Lands: The Hole-in-the-Donut Restoration in the Everglades, Critical Reviews in Environmental Science and Technology, 41:S1, 723-739

To link to this article: http://dx.doi.org/10.1080/10643389.2010.530913

Critical Reviews in Environmental Science and Technology, 41(S1):723–739, 2011

ISSN: 1064-3389 print / 1547-6537 online
DOI: 10.1080/10643389.2010.530913

Restoration of Disturbed Lands: The Hole-in-the-Donut Restoration in the Everglades

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*The Hole-in-the-Donut (HID) wetland restoration project was established on former agricultural land inside Everglades National Park, where rock plowing and fertilization had altered the hydrology, structure, depth, aeration, and nutrient content of soils. Following the cessation of farming, highly disturbed HID soils were invaded by dense, nearly monospecific stands of Brazilian pepper (*Schinus terebinthifolius *Raddi). Initial efforts to restore Brazilian pepper-dominated areas failed, and only complete removal of the substrate down to the surface of bedrock was successful. Complete soil removal resulted in the restoration of a plant community dominated by native wetland plants. Following restoration, initially very shallow soils gradually deepened as marl accreted as due to the activities of periphyton. By 15 years postrestoration, an average of 3.7 cm of soil had developed. Initially low nitrogen concentrations increased following restoration, whereas phosphorus was converted to organic forms and diluted by the accumulation of marl. The result of these changes was a gradual switch from nitrogen limitation to phosphorus limitation, eventually mirroring the situation in adjacent undisturbed wetland sites. Complete substrate removal, as used in the HID, could be used to restore other areas of the Everglades degraded by nutrient enrichment.*

KEYWORDS: Everglades, N:P ratio, nitrogen, nutrients, phosphorus, wetland restoration

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INTRODUCTION

Successful restoration of severely degraded ecosystems may require very high levels of effort to reestablish historic conditions (National Research Council, 1992). In some cases degradation may alter abiotic conditions sufficiently that a threshold is crossed such that reversal becomes much more difficult or impossible (Lindig-Cisneros et al., 2003; Whisenant, 1999). The Hole-in-the-Donut (HID) wetland restoration project was established on former agricultural land inside Everglades National Park. The most highly disturbed areas of the HID were rock plowed, which altered the hydrology, structure, depth, and aeration of soils. Subsequent fertilization dramatically increased soil phosphorus concentrations. Following the cessation of farming, highly disturbed soils were typically invaded by dense, nearly monospecific stands of Brazilian pepper (*Schinus terebinthifolius* Raddi). In this paper we describe efforts to restore disturbed lands in the HID and the vegetation community, soil depth, and nutrient dynamics in restored areas.

HISTORY OF FARMING IN THE HOLE-IN-THE-DONUT

The HID (Figure 1) was initially excluded from inclusion in the Everglades National Park due to its importance as an agricultural area. Approximately 8,900 ha of the HID were originally excluded from the park (Grunwald, 2006), though only a portion of this area was actually farmed.

Farming had begun in the HID by the beginning of the 20th century. There are historical accounts of small farms operating in the marl prairies of the finger glades traversing Long Pine Key as early as the first decade of the 1900s. Taylor (1979) described one such farm as growing vegetables and a few livestock on a small plot of prairie. The Old Ingraham Highway reached Royal Palm by 1915, reducing the travel time from Homestead to Royal Palm Hammock (at the eastern edge of the HID) to a few hours rather than the 3–4 days it had previously taken (Small, 1916). This improved access and increased the influx of farmers, and Loope and Dunevitz (1981) described relatively large areas at the western end of the HID and along the Old Ingraham Highway as having been farmed in the 1920s and 1930s.

By 1940, when the first known systematic aerial photographs of the area were taken, there were farmed areas scattered irregularly around the HID (Figure 2). At that time, farming was limited to the deeper marl soils found in areas of prairie glades and approximately 935 ha of the HID were farmed (Serra, 2009). Many of these areas occurred in finger glades passing through higher areas of pine rockland, such that the fields of this era are mostly irregularly configured to follow the areas of marl soil. Only in the southeastern section of the HID, along the Old Ingraham Highway, and on

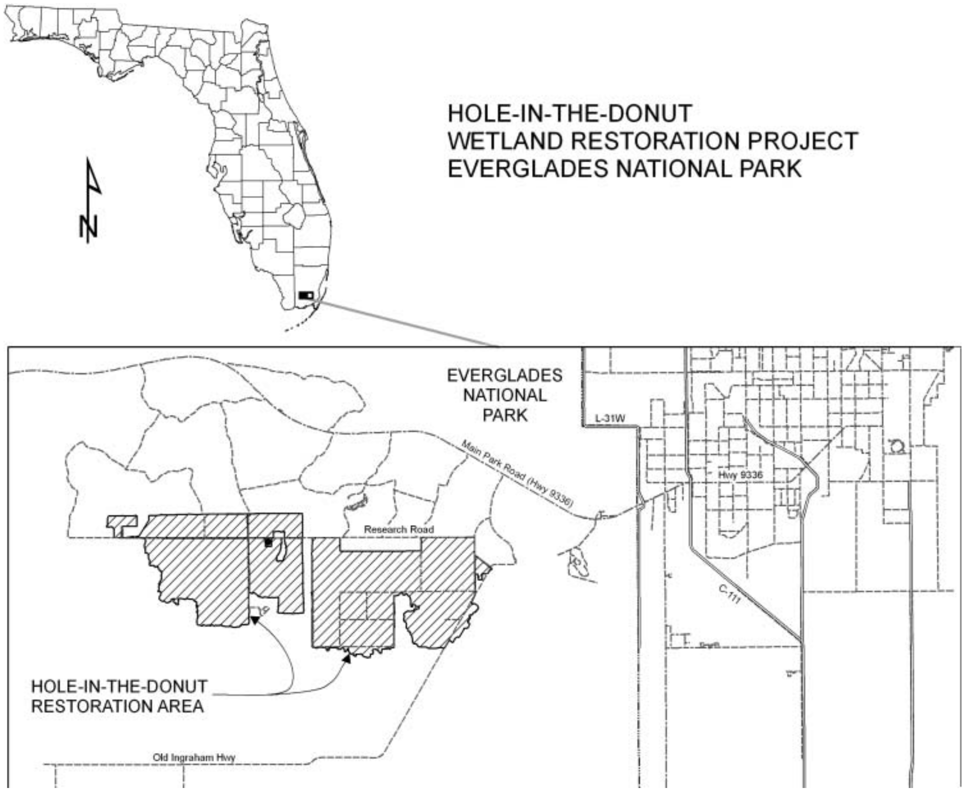

FIGURE 1. Location of the Hole-in-the-Donut Wetland Restoration Project. Diagonal shading illustrates the area of the HID that will be restored by clearing and scraping.

the extreme western end of the HID were there areas of marl soil extensive enough for large rectangular fields to be established.

A land use map of the HID constructed from 1952 aerial photographs (Figure 3) shows that by then many of the areas that had been farmed previously had been abandoned. Within the HID, land slopes to the south and east, and areas in the eastern and southern parts of the HID were too wet to support reliable crop production. Even with the construction of the Madiera ditches south and east of the Old Ingraham Highway, it was apparently not possible to drain the marsh sufficiently for agricultural production, and the one area near the ditches that was tilled was quickly abandoned (Simmons and Ogden, 1998). Prior to rock plowing, farming in the northern, higher elevation portions of the HID was confined to irregular fields within the glade areas of prairie, where soils were deep enough to be tilled. These areas were lower and wetter than the surrounding pine rockland.

By the mid 1950s techniques for rock plowing limestone had been developed. Rock plowing uses tractors and plows to crush the limestone

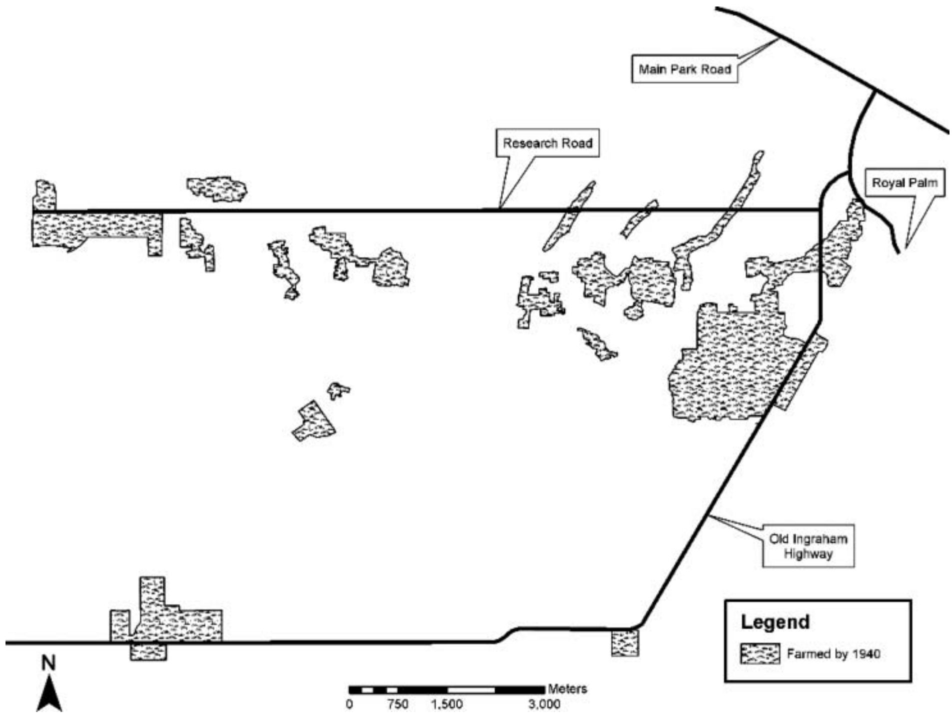

FIGURE 2. Areas of the HID farmed by 1940, determined by photointerpretation of aerial photographs (Serra, 2009).

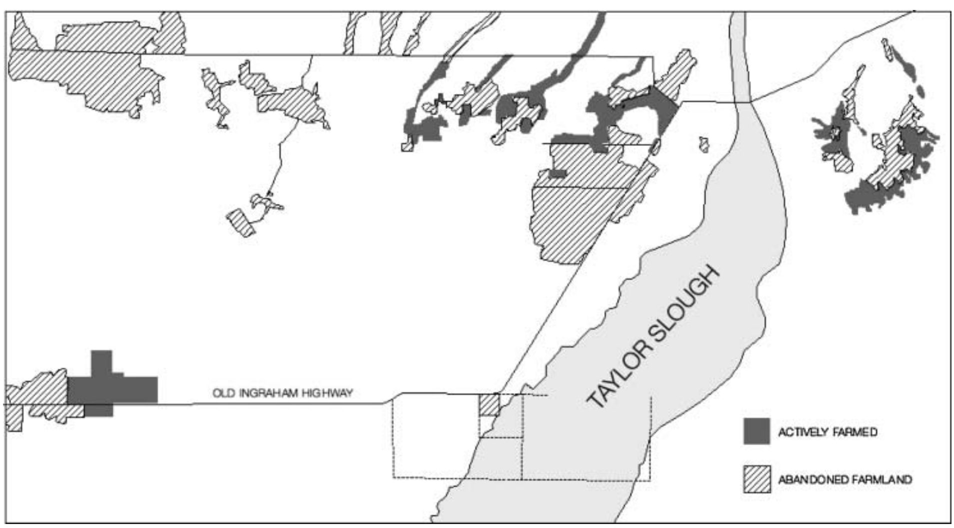

FIGURE 3. Actively farmed areas and areas of abandoned farmland in the Hole-in-the-Donut, 1952 (interpreted from aerial photographs, source unknown).

bedrock into small particles and mix it with any overlying marl or organic soil, creating a new soil typically about 20 cm deep (Ewel et al., 1982). Rock plowing allowed farming of the higher elevation pine rockland areas along the northern edge of the HID. Besides providing a deeper, better drained soil layer for farming, rock plowing leveled out elevation differences between rockland and finger glades and allowed farmers to cultivate large rectangular fields.

Some rock-plowed areas were farmed only briefly. In particular, the area around the former Nike missile base was farmed for less than 10 years after being rock plowed. Shortly after it was rock plowed, the farmer went bankrupt and then the federal government took over the site for use as a Nike missile base. Comparison of conditions in this area with those in areas that were farmed much longer can provide information on the cumulative impacts of fertilization and other ongoing farming activities.

Initially, the park was prohibited from using condemnation to acquire land in the HID as long as the land was being used for agricultural purposes. In 1970, Congress removed the prohibition on condemnation of land within the HID. The threat of condemnation led landowners to sell their property to the park, and by 1975 the park had acquired the last properties in the HID and farming ended. As a result of this land being added to the park, about 1,700 ha of rock-plowed land was removed from agriculture during the period from 1973 through 1975 (Loope and Dunevitz, 1981).

IMPACT OF FARMING ON SOILS

Prior to farming, HID soils could be classified by the depth of marl, or the landscape position on the Miami-Rock Ridge (U.S. Department of Agriculture [USDA], 1996). All HID soils are calcareous, such that the pH of disturbed rock-plowed and non-rock-plowed land in HID was 7.9, and HID restored lands had a pH of 7.8 (Li and Norland, 2001). Most of the land farmed in the HID was originally either muhly or sawgrass prairie (Loope and Dunevitz, 1981). The shallow, non-rock-plowed marl soil under sawgrass vegetation was classified as Perrine marl in 1958 soil survey (USDA, 1958). However, based on 1996 soil survey, this group of soils could be classified as Biscayne marl if the limestone bedrock had a depth ranging from 1 to 20 inches or Perrine marl if the lime stone bedrock occurred at a depth of 20–40 inches (USDA, 1996).

The southeastern portion of HID lies in proximity to Taylor Slough, and would have had soils typical of the Perrine Series, that is course-silty, carbonatic Typic Fluvaquents (USDA, 1996). This silt loam is poorly drained to very poorly drained, with an A-horizon of less than 10 cm, and a Cg horizon is of an angular blocky structure atop the soft, porous, oolitic limestone. There would have been no need to rock plow these soils, as they were deep enough to farm. Biscayne soils are similar, however, the hard oolitic limestone is described at 15 inches, and therefore it is likely these areas were rock plowed. This was probably typical of most HID marl prairie areas.

About 10% of the rock-plowed area of the HID was pineland prior to rock plowing (Loope and Dunevitz, 1981). In the slightly higher elevated pine rockland ridge were the very shallow, non-rock-plowed soil that was classified as Rockdale in 1958 soil survey (USDA, 1958), and closely resembles the Cardsound Series description today (USDA, 1996). There is only an A-horizon of 0–4 inches that forms an abrupt irregular boundary above the hard limestone bedrock (USDA, 1996). This Lithic Udorthent is a well drained silty clay loam, with friable weak fine and granular structure, with approximately 12% gravel.

Rock plowing, using tractors and plows to crush the limestone into small particles and mix it with any overlying marl or organic soil, had a dramatic impact on the soils of the HID. At about 20 cm deep, the rock-plowed soil was deeper, better drained, better aerated, and likely more nutrient-rich than the preexisting natural soils (Ewel et al., 1982). Rock-plowed Rockdale soils were renamed as Krome soil series in 1996 soil survey (USDA, 1996). Krome soils are anthropogenic, created from other soil types by rock plowing, with a gravelly loam Ap underlain by oolitic limestone bedrock (USDA, 1996). Rock plowing disrupts any soil horizonation that once existed between the A and C horizon (if present), and creates an extremely friable soil of weak granular structure with 35–60% limestone fragments. These created soils are well drained, shallow (0–7 inches), and moderately permeable (USDA, 1996). Typically, rock plowing increases soil volume (Meador, 1977), leading to a decrease in bulk density and an increase in the soil surface elevation.

In addition to the alterations of physical structure resulting from rock plowing, cultivated soils that were once low in nutrients now contain higher nutrient concentrations as the result of fertilization (Doren et al., 1990). The longer soils were fertilized, the higher the nutrient inputs, which may lead to higher residual phosphorus concentrations. Shortly after farming of the HID ceased, Orth and Conover (1975) found that, on average, farmed soils in the HID were about 500% higher in total P, 150% higher in water soluble P 17% higher in total K and 12% higher in nitrate N, whereas total N decreased 30%. Nearly 25 years after the cessation of farming, Li and Norland (2001) found 3.5 times greater concentrations for total P in rock-plowed soils when comparisons of rock-plowed soils to non-rock-plowed soils were made (Figure 4). At 1140 mg/kg, rock-plowed lands contain about 5 times higher total P than the 219 mg/kg total P concentration observed in south Everglades marl soils (Chen et al., 2000). The combination of shorter hydroperiod, better drainage and aeration, and higher phosphorus concentrations, as found in areas that had been farmed, created an environment favorable to the invasion and continued dominance of Brazilian pepper (*Schinus terebinthifolius* Raddi).

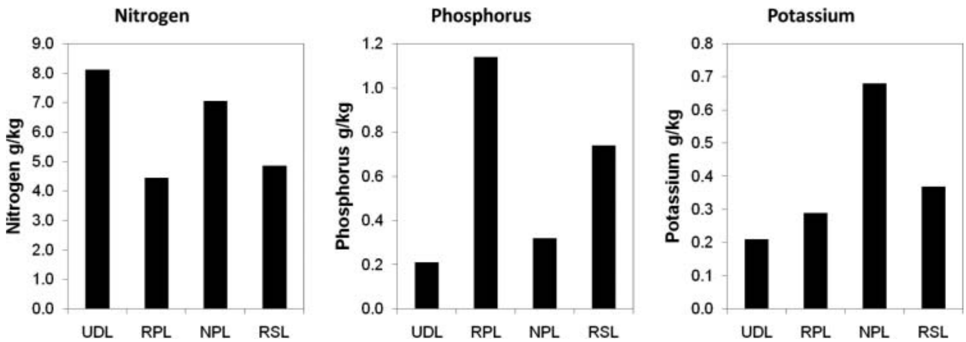

FIGURE 4. Nitrogen, phosphorus, and potassium concentrations in soils from undisturbed (UDL), rock plowed (RPL), non-rock-plowed farmland (NPL), and restored areas (RSL) of the Hole-in-the-Donut (Li and Norland, 2001).

Marl soils such as those originally found in much of the HID accrete due to calcite deposition resulting from the activities of periphyton. The growth of periphyton is disrupted by improved drainage and by elevated nutrient concentrations. The rock-plowed soils that develop on former farmland support little periphyton; thus, there is little or no marl deposition in these areas (O'Hare, 2008).

Non-rock-plowed soils were tilled and furrowed. Tilling may aerate the soil, but does not add as much pore space or increase the elevation to the extent that the rock plow integrates the crushed limestone fragments. Since the rock plow was not necessary in deeper soils, these soils are not as well drained as rock-plowed sites, even after farming. Non-rock-plowed farmed soils in the HID were also found to be lower in total phosphorus than rock-plowed soils (Li and Norland, 2001). Despite the lesser degree of disturbance than rock-plowed soils, farming has altered non-rock-plowed soils sufficiently to affect natural processes. For example, where furrows remain, they act as a barrier to fire, disrupt sheet flow and alter hydrology.

POSTFARMING VEGETATION COMMUNITIES

Following the cessation of farming, farmed areas were quickly invaded by a diverse collection of plants (Ewel et al., 1982). The combination of shorter hydroperiod, better drainage and aeration, and higher phosphorus concentrations, as found in areas that had been farmed, created an environment favorable to the invasion and continued dominance of Brazilian pepper. The postfarming vegetation communities that developed often bore little resemblance to prefarming vegetation communities (Loope and Dunevitz, 1981).

One difference is that the postfarming vegetation of rock-plowed fields often develops into a forest, even on sites that were dominated by herbaceous vegetation prior to farming (Ewel et al., 1982).

Loope and Dunevitz (1981) described successional sequences of vegetation on formerly rock-plowed sites. They found that the initial assortment of colonizers is dominated by weedy herbaceous species. Within a few years, the initial stages dominated by herbaceous species gave way to vegetation increasingly dominated by native and exotic shrubs. Wind-dispersed shrubs became established in the first year—and can become locally dominant by the third year. Prior to the introduction of Brazilian pepper, transitional shrub communities were replaced by late successional communities dominated by *Myrica cerifera*, *Ilex cassine*, and *Persea borbonia*. At one time these species dominated 30–40-year-old late-successional communities along the southeast margin of the HID (Loope and Dunevitz, 1981).

Since the introduction of Brazilian pepper, most highly disturbed farmed sites have come to be dominated by Brazilian pepper. Ewel et al. (1982) found that by 8+ years after the cessation of farming, Brazilian pepper was an important part of the vegetation community of each location they examined. Loope and Dunevitz (1981) found that Brazilian pepper was present in scattered groups by the third year after farming ceased, and it continued to invade for or more 15 years, by which time had formed nearly pure stands. With time, it came to dominate vast areas of the HID. Ewel et al. (1982) found that Brazilian pepper came to dominate even lands that had not been farmed for 30 years or more, and some lands that were never rock plowed. The HID wetland mitigation bank project area covers more than 2,400 ha (Figure 1), nearly all of which is, or was before restoration, dominated by dense Brazilian pepper. Live Brazilian pepper is not flammable and well-established communities of Brazilian pepper will not burn. Once dense, Brazilian pepper becomes established in an area, fire is excluded.

Ewel et al. (1982) identify the importance of mycorrhizae (i.e., plants with fungi symbiotic associated with their roots that aid in nutrient uptake) as one of the key changes between undisturbed and postfarming vegetation communities. Mycorrhizal plants are uncommon in the plant communities characteristic of the seasonally flooded, poorly aerated soils in their natural state. One reason for this is that mycorrhizal fungi are obligate aerobes, and many of the natural soils are too wet for them to survive. Rock plowing, however, increases soil aeration and allows mycorrhizal fungi to survive, thus favoring plants with mycorrhizal roots.

ATTEMPTS TO MANAGE OR RESTORE HID FARMLAND

Vast areas of abandoned farmland in the HID came to be dominated by the exotic Brazilian pepper, which invaded even lands that had not been farmed for more than 30 years, and some that were never rock plowed (Ewel et al., 1982). Dominance by Brazilian pepper resulted in the disruption of natural plant and animal community organization and function, increased productivity and altered food chains (Curnutt, 1989; Doren and Whiteaker, 1988; Ewel et al., 1984; Krauss, 1987).

As postfarming vegetation communities came to be increasingly dominated by exotic species such as Brazilian pepper (*Schinus terebinthifolius*) or shoebutton ardisia (*Ardisia elliptica*), Everglades National Park initiated efforts to manage the vegetation of formerly farmed areas of the HID. The ideal management goal, per National Park Service management policies, would be the restoration of natural conditions and vegetation. By 1975, management documents reflected the realization that control of exotic plants, particularly Brazilian pepper, had become the priority (Anonymous, 1975).

A number of techniques for managing exotic plants and restoring native vegetation were attempted. These included planting pine seedlings or seeds; spreading prairie or pine litter; planting grass seed; transplanting wiregrass and cordgrass clumps; seeding with sawgrass; seeding with palmetto; mowing, rolling, burning, disking, bulldozing, partial, or complete soil removal; and mounding soil to create an artificial hammock. Attempts to establish other vegetation without controlling or removing Brazilian pepper uniformly failed, as it outcompeted the plantings. Effort to control Brazilian pepper using mechanical, physical, or chemical means were initially successful, but mostly failed to achieve long-term control. For example, bulldozing (Loope and Dunevitz, 1981) or bulldozing and burning (Ewel et al., 1982) initially eliminated Brazilian pepper from nearly pure well-established stands, resulting in a vegetation community dominated by other weedy species. With time, this community was replaced by a Brazilian pepper-dominated one.

Bancroft (1973) described attempts made during the 1970s to establish slash pine on HID land that had been farmed until the 1940s and then abandoned. In 1972, seed was collected using a tree shaker, harvested, and grown by the Florida Department of Agriculture and Consumer Services, Division of Forestry. A bulldozer was used to remove Brazilian pepper and clear shrubby vegetation from the approximately 1000 acre study site. Disturbed soil was left in place. Native transplants, bareroot seedlings, speedlings, and potted pines were introduced to determine whether slash pine could successfully be established. Speedling and native transplant survival after 6 months was 11% and 0%, respectively. After 3 years of reestablishment, survival of bareroot hand plantings was 3% and potted pines was 25%. The outcome was unsuccessful and it was determined that planting slash pine was not a practical way to reclaim disturbed land in the HID.

Not only were intensive management practices such as bulldozing expensive and out of step with most resource managers' idea of management appropriate on national park land, they resulted in disturbed sites that were especially susceptible to reinvasion by Brazilian pepper (Ewel et al.,

1982) and failed to achieve long-term goals. Following attempts to manage Brazilian pepper-dominated areas by bulldozing, Loope and Dunevitz (1981) concluded there was no possibility of restoring the original vegetation of rock-plowed areas.

THE SUCCESSFUL WETLAND RESTORATION STRATEGY

The one technique that successfully restored wetland on former rock-plowed sites within the HID is the mechanical removal of woody vegetation followed by the complete removal of disturbed soil. An early large-scale experiment tested soil removal to determine whether partial soil removal was sufficient to accomplish Brazilian pepper control and restoration, or whether complete soil removal was necessary. Dalrymple et al. (2003) found that partial soil removal led to an initial increase in the number and coverage of hydrophytes, but within a few years the overstory vegetation of the area had reverted to a monoculture of Brazilian pepper. In contrast, they found that removing all of the rock-plowed soil layer, down to bedrock, led to conditions that favored the recolonization and persistence of natural wetland vegetation that was not reinvaded by Brazilian pepper. Following restoration, the plant community of the complete soil removal areas undergoes succession that is dominated with natural wetland plants (Doren and Whiteaker, 1988).

The appeal of complete soil removal, despite its cost, is that it results in restoration of natural site conditions, such that native wetland plant communities establish and maintain themselves without planting and with only very limited management. Removing the altered, rock-plowed soil removes nutrients, lowering nutrient availability, and lowers the surface of the ground, increasing the hydroperiod. Brazilian pepper and other invasive exotic species do not generally thrive in the restored areas, except in pockets of disturbed soil remaining in filled in solution holes. Thus only very limited exotic plant control is required to maintain desirable communities of native wetland plants in the restored areas.

Monitoring of restored areas has found that within a few years of restoration, native wetland species dominate with only a few exotic plant species present and low total cover of exotics. Monitoring conducted in the fall of 2006 (O'Hare, 2008) found that the percentage cover of high-affinity wetland plant species (obligate and FacW species) in restored areas of the HID ranged from 56 to 92%. The lowest cover of wetland plant species (56%) occurred on a slightly higher elevation site adjacent to intact pine rockland. Except for this site, the percentage cover of high-affinity wetland plant species was above 79%. There was no clear relationship between the percentage of cover by wetland plants and the length of time since restoration. Undisturbed sites had a percentage cover of high-affinity wetland species of 60, which is near the low end of wetland percentage cover found in restored sites. In contrast, unrestored areas of Brazilian pepper had only 13% cover of high-affinity wetland species. O'Hare (2008) found that the percentage cover of nonnative species in restored sites was less than 5% and did not differ significantly from the 1% average cover of nonnative plants found in natural vegetation, whereas the average percentage cover of nonnative plants in Brazilian pepper was 64%.

NUTRIENTS IN SOILS OF RESTORED AREAS

After clearing and scraping, restored areas initially have only a very shallow layer of residual soil over limestone bedrock. Only in solution holes is there much residual soil. Although there is no reason to expect the nutrient concentration in residual soil on restored sites to differ from the concentrations present before restoration, the reduction in soil depth greatly reduces the availability of nutrients for plants growth, on a per square meter basis. Presumably reduced nutrient availability is one of the factors contributing to the fact that restored sites become vegetated with native wetland plants, with only limited growth of exotics such as Brazilian pepper.

Much of the restored area is wet enough to support periphyton. O'Hare (2008) estimated that 72% of the restored area had a hydroperiod longer than 3 months, based on a 15-year average hydrology. Restored areas that support periphyton accumulate marl soil, similar in general characteristics to the soils that existed in the area prior to agriculture following clearing and scraping. Periphyton cover of restored sites increases very rapidly following restoration, exceeding 80% by three years after restoration and reaching the 96% cover characteristic of undisturbed sites by 15 years postrestoration (Inglett et al., 2010). In these periphyton-covered areas, the main soil building process is the precipitation of calcite, as the result of periphyton photosynthesis. Recovery of prerestoration soil depths takes considerably longer than the recovery of periphyton cover (Figure 5). The oldest restoration site in the HID at 15 years postrestoration had accumulated an average of 3.7 cm of soil (Inglett et al., 2010). This soil depth is at the low end of the range (3–7 cm) described as optimal by the Hydrogeomorphic Model of Everglades rocky flats wetlands (Noble et al., 2002). It is therefore likely that soil-related wetland functions are beginning to approach natural conditions by 15–20 years postrestoration. At this rate of soil accumulation it will take nearly 28 years to accumulate 6.7 cm of soil, the depth found in undisturbed areas.

Li and Norland (2001) investigated phosphorus, nitrogen, and potassium concentrations in soils from sites that were rock plowed (unrestored), farmed without rock plowing, restored, or undisturbed (Figure 4). They found that phosphorus concentrations were much higher in rock-plowed (unrestored) and restored sites than in sites that are undisturbed or were farmed without rock plowing (and not restored). Relatively high phosphorus concentrations

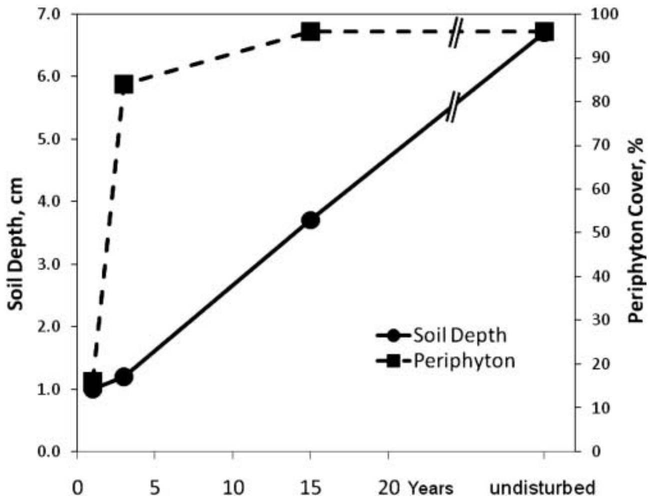

FIGURE 5. Periphyton cover and soil accumulation following restoration (Inglett et al., 2010).

in soils of rock-plowed sites presumably result from additions of phosphorus fertilizer to the homogenized limestone layer from rock plowing, which resulted in the formation of a precipitate that decreased phosphorus solubility and leachability, and thereby retaining added phosphorus in the soil (Orth and Conover, 1975). In contrast, nitrogen concentrations were considerably lower in rock-plowed (unrestored) and restored sites than in sites that are undisturbed or were farmed without rock plowing. Potassium concentrations were somewhat higher in rock-plowed (unrestored) and restored sites than in sites that are undisturbed, but were much higher in sites that were farmed without rock plowing than elsewhere.

Following restoration, as soil accumulates and the soil depth increases, nutrient concentrations change in relation to the inputs and losses for each particular nutrient, as diluted by the increasing volume of soil. Inglett et al. (2010) studied phosphorus and nitrogen concentrations on a chronosequence of sites of varying ages following restoration as a way of approximating nutrient concentration changes following restoration. Our conclusions on postrestoration N and P dynamics are derived from their results, excluding results from sites restored in 2000 and 2001 that had only been farmed briefly after rock plowing.

Total phosphorus concentrations are initially much higher in restored areas than in undisturbed areas and decline with time as bulk sediment accumulates with little input of additional phosphorus (Figure 6). Postrestoration phosphorus dynamics primarily reflect dilution of the initial phosphorus content, as there is no mechanism providing much additional phosphorus input and phosphorus is not particularly mobile in marl soils of the HID. Besides dilution, phosphorus availability further declines postrestoration as available

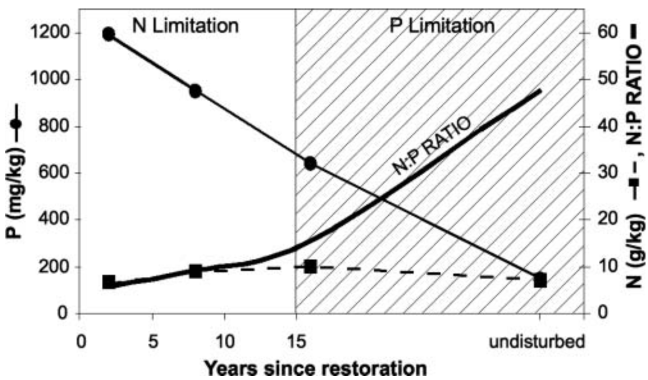

FIGURE 6. Changes in nutrient limitation following restoration. Data are from Inglett et al. (2010), replotted to exclude samples from areas restored in 2000 and 2001 that were farmed only briefly after being rockplowed.

inorganic phosphorus forms are converted to unavailable forms (Inglett et al., 2010).

Following restoration, total nitrogen concentrations in soils of restored sites are initially similar to concentrations in undisturbed sites (Inglett et al., 2010). Total nitrogen concentrations increase with time after restoration, and soils from a 16-year-old restored site (Res89) have higher nitrogen concentrations than those from younger sites or from the undisturbed reference site (Figure 6). The increasing nitrogen concentration with time indicates that in restored sites nitrogen fixation and atmospheric deposition outpaced the rate of soil accumulation. Inglett et al. (2010) found that the undisturbed site they sampled had a lower total nitrogen concentration than the 16-year-old restored site, but Li and Norland (2001) found that total nitrogen concentrations were higher in undisturbed sites than in restored sites. Based on this difference, it is unclear whether nitrogen accumulation will continue to outpace soil accretion in the long run.

Inglett et al. (2010) hypothesized that changes in P and N concentrations following restoration would result in a shift from nitrogen limitation immediately after clearing and scraping to phosphorus limitation as sites recover (Figure 6). Presumably the switch occurs as the N:P ratio increases above a value in the range of 13:1, characteristic of many soils (Cleveland and Liptzin, 2007), to 16:1, characteristic of phosphorus limitation in plant tissues (Koerselman and Meuleman, 1996). Sites with 8 or fewer years postrestoration had N:P ratios below 10, presumably indicating nitrogen limitation. By 16 years postrestoration, the N:P ratio had increased to 15.5, presumably near the transition point from nitrogen to phosphorus limitation. Undisturbed HID sites had soil N:P ratios averaging nearly 48:1, presumably indicating phosphorus limitation.

In contrast with the wetter areas that form the majority of the restored area of the HID, areas of sufficiently high elevation that they have only a very short hydroperiod would be expected to develop soils very slowly as the limestone bedrock weathers and organic matter accumulates (Inglett et al., 2010). Since the higher pine rockland sites that were farmed were rock plowed, and rock plowing lowered the surface elevation of bedrock, only a small fraction of the restored HID is likely to fall into this category. O'Hare (2008) found that only 13% of the presently restored area of the HID has a hydroperiod of less than 1 month, based on 15-year average hydrology. Presumably these areas will develop the thin, rocky soils characteristic of pine rocklands. To date, no studies of postrestoration biogeochemistry have specifically targeted these areas.

UNRESOLVED ISSUES AFFECTING RESTORATION

Restoration of Karst Microtopography

Although an effort is made during restoration to excavate soil from solution holes, formerly rock-plowed areas have little microtopography. Marl prairie areas often have a moderate degree of local microtopography, as the result of dissolution of high areas and marl filling most smaller solution holes. In contrast, pine rockland areas have a very diverse ground surface, with piles of broken rock alternating with flat bedrock areas and solution holes. Unless a means to restore the microtopography of potential rockland areas is developed, it will likely be very difficult to restore the diverse understory typical of an undisturbed pine rockland community.

Restoration of Disturbed Areas Not Dominated by Brazilian Pepper

Within the HID area, there are areas of abandoned farmland that have not become dominated by Brazilian pepper. Examples of these areas include the large areas at the western end of the HID, along the closed section of the Old Ingraham Highway, and in the Long Pine Key finger glades north of Research Road that were farmed in the 1920s and 1930s. Some of these areas have reverted to prairies of muhly and sawgrass (Loope and Dunevitz 1981). Others have remnant furrows or bulldozed swales that have altered the soil elevation, drainage, and hydrology. Typically, these areas are dominated by native vegetation, but the composition and spatial diversity differs from undisturbed areas. For example, an area south of the Old Ingraham Highway that is crisscrossed by bulldozed swales was found to have increased shrub cover on the remaining high spots and sparse spikerush (*Eleocharis cellulosa* Torr.) in the swales (C. S. Smith, personal observation). Still other areas, such as the finger glades north of research road, have become stands of successional hardwood vegetation (Loope and Dunevitz, 1981).

The key differences between these areas and areas that have come to be dominated by Brazilian pepper have not yet been positively identified. Factors likely to contribute to the difference include the timing of abandonment (before vs. after Brazilian pepper invasions of the region) and differences in the extent of soil disturbance and fertilization (rock plowed or not, amount and nature of fertilizer applied). Studies are presently being initiated to investigate the role of these factors in determining the postabandonment vegetation.

Although complete soil removal results in the restoration of formerly farmed sites, it is a highly intrusive, expensive approach. It may be possible to develop less invasive, less expensive methods for restoring sites that have not become completely dominated by Brazilian pepper, particularly if these areas have soils that are less altered than those where Brazilian pepper dominates. Conversely, in other areas of the Everglades where soils are highly nutrient enriched, complete soil removal may be a viable restoration technique.

CONCLUSION

Only complete substrate removal accomplished long-term restoration of Brazilian pepper-dominated areas on highly disturbed, nutrient enriched soils left over from previous farming in the HID area of Everglades Nation Park. Complete soil removal resulted in the restoration of a plant community dominated by native wetland plants. Following restoration, soils were very shallow and marl gradually accreted as the result of the activities of periphyton. By 15 years postrestoration, an average of 3.7 cm of soil had developed, which corresponds to the low end of the optimal range (3–7 cm) described by the Hydrogeomorphic Model of Everglades rocky flats wetlands (Noble et al., 2002). Initially low nitrogen concentrations increased postrestoration, whereas phosphorus was gradually converted to organic forms and diluted by the accumulation of microbially produced marl. The result of these changes was a gradual switch from nitrogen limitation to phosphorus limitation, eventually mirroring the situation in adjacent undisturbed wetland sites. Complete substrate removal, as used in the HID, could be used to restore other areas of the Everglades degraded by nutrient enrichment.

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