Toxic aqueous discharge of iron and sulphur from spoiled coal mined lands and its control by phytostabilization process

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Toxic aqueous discharge of iron and sulphur due to acid mine drainage causes soil and water pollution. Many countries with unoperating as well as functional mining industries face this problem. In north-eastern India, coal mining has severely degraded much of the agricultural land by impairing soil, plant diversity and water quality. A study was conducted in coal mined out area of Jaintia hills, Meghalaya (north-eastern India) to eliminate toxic aqueous discharge (iron and sulphur) and restore the soil fertility of affected land for sustainable crop production. The treatment of acid mine drainage through phytostabilization and soil amendment with agricultural lime and organic manures reduced sulphate from 22 to 5 mg kg^{-1} and soluble iron from 476 to 109 mg kg^{-1} of surface soil. The soil pH increased by 1.4 unit from its initial value and concentration of plant nutrients like N, P, K and microbial biomass content reached optimum fertility levels. Soluble iron and sulphate in drainage water reduced considerably by 26% and 49% respectively, with concurrent increases in water pH (3.2 to 7.2). Rice grain yield in the mined out area reached about 1320 kg ha^{-1} after reclamation as compared 1920 kg ha^{-1} in non-mined area. The adaptation of native plant species (*Citrus reticulate*, *Prunus napalensis* and *Pyrus communis*) was about 70%. Afforestation with native fruit plant species and ferns/grasses, soil amendment using lime and organic manure, and channelling of seepage water for checking acid mine drainage contamination of water bodies and crop fields were some of the measures that were effective in mitigating toxicity. Phytostabilization helped in reversing the trend and restoring soil fertility and plant growth due to a rise in soil organic matter, nutrient availability as well as biological activities.

Keywords: Acid mine drainage, coal mining, north-eastern India, phytostabilization.

COAL production in the Asia Pacific region has grown tremendously and accounts for over 67% of the total global production (2011) as compared to about 27% in 1981 (ref. 1). Out of 861 billion tonnes global coal production, India accounts for 286 billion tonnes. Other countries with major chunk of coal resources are USA, China, Australia, Indonesia and South Africa. Over 60% of coal resources in India are located in forest areas[2]. Coal mining wastage disrupts the soil fertility components, altering water quality and affecting vegetation leading to destruction of vast amounts of land. These operations convert fertile land into wasteland and pollute land, air and water. Presently, 119 abandoned coal mines exist in about 2.13 million hectares of coal reserves in India. Land degradation due to coal mining operations is reported to be at the rate of 4 ha per million tonne of coal production. At this rate, coal mining operations alone would continue to render more than 1400 ha unproductive every year[3].

Phytostabilization is a common practice to revegetate spoiled mine lands to prevent soil erosion and to immobilize toxic contaminants in soils[4]. Ideal plants for this method use metal-tolerant, drought-resistant, fast growing plants with fibrous root systems that have rooting depths of about 30–60 cm and can also grow in nutrient-deficient soils[5]. The advantages are that the technique is inexpensive soil does not need to be removed, ecosystem restoration is enhanced, and disposal of hazardous materials or biomass need not be disposed. Stabilization is primarily due to the effects of soil amendments and planted vegetation which control bulk soil migration and/or prevent contaminant migration through phytosequestration. The application of lime, organic matter and fertilizer fits well with this technique as it provides necessary fertilizing agents and aids in establishing microbial colonies.

Meghalaya, one of the eight states of north-eastern (NE) India, is bestowed with rich natural vegetation as well as large reserve of mineral resources including coal deposits. Coal deposits occur as thin seams, which range from 0.30 to 1.5 m in sedimentary rock, sandstone and shale of the Eocene age[6]. It is estimated that 562.8 million tonnes of coal in 20 major or minor deposits are distributed throughout the state. Most of the coal deposits are small and isolated and not amenable for scientific mining in the organized sector. As a result, in most parts of the state, coal is being indiscriminately mined in unscientific ways, causing large-scale destruction and deterioration to the natural eco-system[7]. Soil disturbance associated with mining activities causes the loss of large quantities of soil organic carbon, limits microbial activity, lowers nutrient status, reduces water holding capacity, and pH, increases iron (Fe) oxides and sulphates, and causes erosion and leaching, which severely inhibits restoration of soil nutrient cycling. Abandoned mines produce copious amounts of acid due to acid mine drainage (AMD) that eventually flows into lakes, streams and rivers. Soil is also affected by AMD and becomes unsuitable for crop production[8].

While mining sites are severely degraded and are unsuitable for conventional agriculture use, there is great potential to restore such lands into more normally functioning ecosystems. Furthermore, these degraded lands

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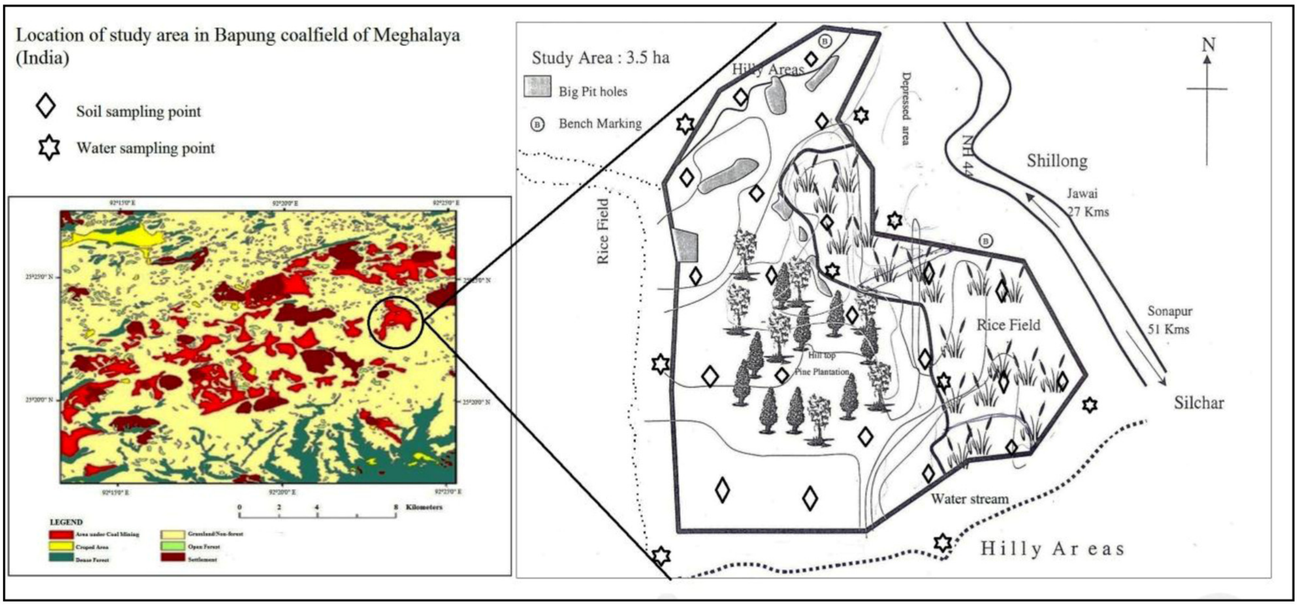

Figure 1. Study area of abandoned coal mine land in Bapung coalfields of Meghalaya, India.

have the potential to store carbon and other nutrients, such as nitrogen and phosphorus. This communication presents model considerations on the phytostabilization process for elimination of spoiled coal mined lands due to toxic aqueous discharge of iron and sulphur through AMD, and to restore soil fertility for sustainable crop production.

The present study was conducted during 2005–2013 in Meghalaya (North Eastern India) that has a total geographical area of 22,429 sq. km located between Bangladesh in the south and the Brahmaputra valley in the north. Jaintia hills district is the largest producer of coal where nine coal deposits are spread out in Bapung, Lakadong, Jarain, Lumshnong, Malwar, Sutanga, Ioski, Chyrmang and Mutang area. About 60 villages have been affected by coal mining degradation. Bapung coalfield (25°24′0″N and 92°23′0″E) has the largest coal deposit (34 million tonnes) covering an area of 12 sq. km. The area represents undulating surface with elevation varying from 1073 to 1370 m above mean sea level. About 3.5 hectare abandoned coal mine land, from this area, under three different topographic situations was selected for study (Figure 1). The soil and water quality of the study area have been badly affected due to leaching of AMD from mines and spoils and silting by coal and sand particles. The climate is temperate and August is the hottest month with highest average temperature of 24.5°C, falling to 7.8°C in January. The average rainfall amounts to 2800 mm per year.

The study areas were reclaimed using agricultural lime and organic manure to improve the soil condition. Fruit plants, ferns and grass were planted to produce optimum biomass. A separate drainage system was made for safe disposal of run-off from coal pits to avoid contamination of the main agriculture land.

Biological reclamation began with the selection of suitable plant species which were native to the place, hardy in nature, drought-resistant, fast growing and could be grown in nutrient-deficient soils. Well-adapted species establish self-sustaining cover which require little or no-maintenance activities[9–11]. Based on plant survey and consultation with horticulture department of the area, three fruit plants namely, mandarin orange (*Citrus reticulate*), sohiong (*Prunus napalensis*) and pear (*Pyrus communis*) were found suitable for the study. One-year-old seedlings of these fruit plants were transplanted (spacing of 4.5 m × 4.5 m) in both upland and medium land. During planting, 10 kg of compost, 90 g nitrogen (N), 25 g phosphorus (P), 60 g potash (K), 30 g difuron insecticide, and 3 kg of agriculture lime ($CaCO_3$: 36%) were mixed with the soil of each pit (0.5 m × 0.5 m × 0.5 m). Some of the local ferns and grasses were also transplanted at both sides of drainage and around fruit plantation pit. In the lowland rice fields, reclamation was done by application of manure, fertilizer and lime (25% of LR). The amount of FYM: lime: N–P–K fertilizer was applied at the rate of 60 : 125 : 2.5–4.0–0.5 kg per 100 m^2.

Representative soil samples (0–30 cm) were collected from the study area for the study. On the basis of the study, lime requirement (LR) was calculated as 30 t $CaCO_3$ ha^{-1}. It was estimated on the basis of exchange acidity and percentage of base saturation of soil using modified Woodruff's buffer method[12]. The soil samples were dried, sieved (2 mm) and analysed for pH, soil texture, organic carbon, potassium, phosphorus and iron following standard procedures[13]. Water samples were analysed for

Table 1. Soil characteristics of coal mined-out area during pre- and post-reclamation

Land situation	pH	Organic carbon (%)	Available nitrogen (kg ha^{-1})	Available phosphorus (kg ha^{-1})	Available potash (kg ha^{-1})	Sulphate content (mg ha^{-1})	Soluble iron (mg kg^{-1})	Soil particle size (%)		
								Sand	Silt	Clay
Upland										
Pre-reclamation	4.50	1.05	184	4.69	101	16	347	51.98	15.01	33.00
Post-reclamation	5.35	0.84	251	11.24	161	11	109	–	–	–
Medium land										
Pre-reclamation	4.40	0.79	168	7.76	157	22	476	68.64	11.35	20.00
Post-reclamation	5.43	1.11	396	27.0	289	13	116	–	–	–
Lowland										
Pre-reclamation	4.10	0.32	64	5	181	18	421	42.36	24.92	32.72
Post-reclamation	5.50	0.40	329	24.5	224	5	147	38.48	24.64	36.88
CD ($P = 0.05$)	0.50	0.47	189	13	85	7	114	–	–	–

Table 2. Microbial biomass carbon content in soils of coal mined out areas after reclamation

Land situation	Microbial biomass (μg g^{-1})	
	Soil depth: 0–15 cm	Soil depth: 15–30 cm
Pre-reclamation	27.9 (±3.5)	13.9 (±2.4)
Post-reclamation		
Upland	94.1 (±7.8)–118.5 (±8.2)	76.7 (±6.7)–94.1 (±7.9)
Medium land	48.8 (±4.7)–62.7 (±5.3)	38.3 (±3.7)–48.8 (±4.4)
Lowland	90.6 (±7.2)	62.7 (±6.4)

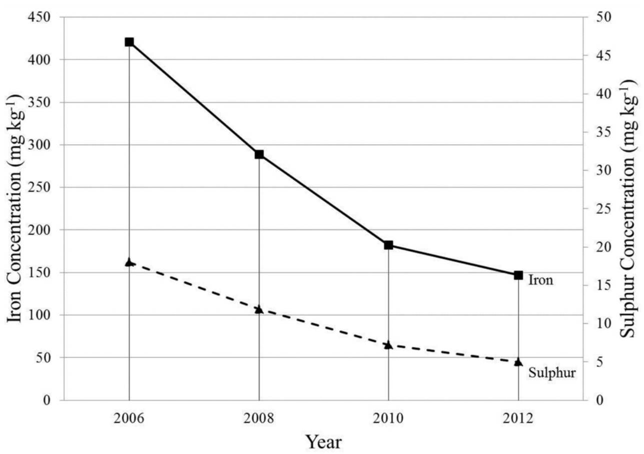

Figure 2. Sulphate and iron content in soil surface during reclamation period.

various physico-chemical parameters using standard methods recommended by American Public Health Association[14]. The pH was tested in the field during sample collection using portable pH meter (Eutech Instrument). Soluble iron was analysed using atomic absorption spectrophotometer (Perkin Elmer AA200). Sulphate content was determined by the extent of turbidity created by precipitated colloidal barium sulphate suspension.

Soil characteristics at the beginning and after eight years (2005–2013) of reclamation are given in Table 1. At the beginning of the study, soil was adversely affected due to mining. It was sandy, reddish brown in colour, strongly acidic in reaction (pH 4.1 to 4.5) with low to high contents of organic matter (0.32 to 1.05%). Available phosphorus and potassium content was low ranging from 5.0 to 7.76 kg ha^{-1} and 101 to 181 kg ha^{-1} respectively. Soluble iron (347–476 kg ha^{-1}) and sulphate content (16–22 kg ha^{-1}) of soil were comparatively very high than the non-coalfield area. Coal contains 2.02–9.2% moisture, 2.6–7.8% ash, 46.2–52.3% carbon and 3.2–7.1% sulphate.

The two toxic elements on coal mine spoils were iron (Fe) and sulphate (SO_4). Low pH was another major determinant which indicates the acute acidity of the soil. Microbial biomass content (MB-C) was also very low (13.9–27.9 μg g^{-1}) due to low organic carbon and strongly acidic pH. Some other researchers also reported such changes and their impact on the soil properties due to mining[15,16]. The phytostabilization processes were effective in raising the pH of soil surface from 4.1 to 5.5. Concentration of plant nutrients like N, P and K increased from 64 to 396 kg ha^{-1}, 4.7 to 27 kg ha^{-1} and 101 to 289 kg ha^{-1} respectively, in all the land situations. Sulphate and iron concentration of surface soil were significantly lowered from 22 to 5 mg kg^{-1} and 476 to 109 mg kg^{-1} respectively. The concentrations of Fe and SO_4 in experimental rice plots contaminated with coal spoils are plotted from 2005 to 2012 (Figure 2). A steady decrease in concentrations of Fe and SO_4 can be noted from the second year of reclamation.

A distinct variation on MB-C in soils at 0–15 cm depth under three different topographic situations was observed (Table 2). More MB-C content was observed in amended soils of upland in comparison to that of medium lands. Reclaimed lowland rice field had elevated effect on microbial biomass carbon content (90.6 μg g^{-1}) at 0–15 cm soil depth. Nutrient cycling is very closely linked to soil microbe activity. Carbon, N and P are reused within an ecosystem due to the metabolic activity of plants and soil microbes. Carbon and nitrogen cycles in

Table 3. Survival rate of fruits tree at study site of mined-out areas after reclamation

Plant species	Number of fruit plant planted	Survival of plants		Growth of plants (length in cm)
		Number	Per cent	
Prunus napalensis	185	98	53	25–35
Citrus reticulate	185	136	73.5	40–60
Pyrus communis	85	71	83	40–70
Total	455	305	69.84	–

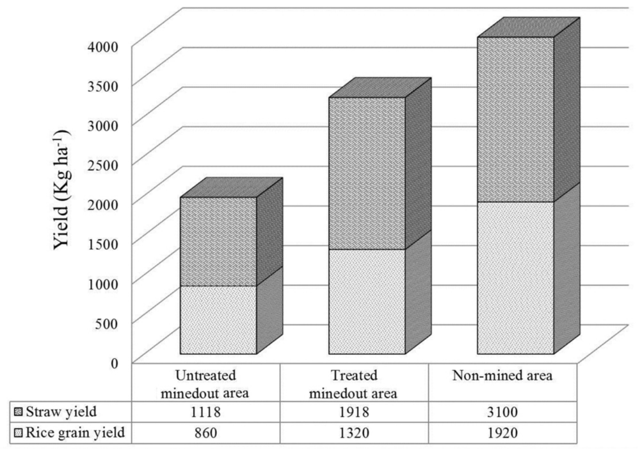

Figure 3. Rice productivity during reclamation in the coalfield area of Meghalaya, India.

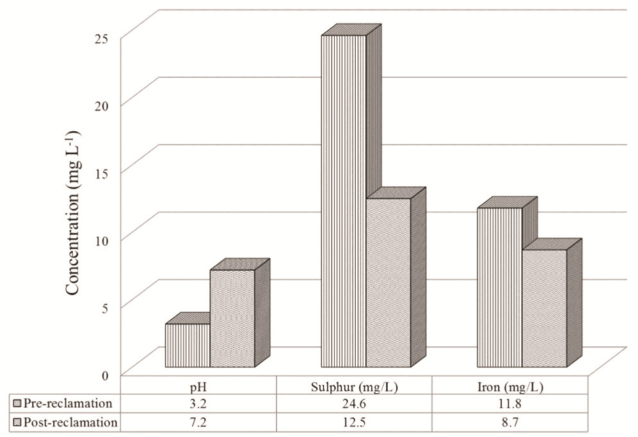

Figure 4. Change in pH, sulphate and iron content of the drainage water from coal mine area.

particular are disrupted as soil microbe populations declines and must be re-established during reclamation[17]. Higher value of microbial biomass indicates better soil quality and enhanced nutrient cycling in agroforest ecosystem. Lime addition helped in reducing the iron mobility in soils and their accumulation in the plant. Organic amendments such as use of manures increase the soil pH and serve as a microbial inoculum[18,19]. In general, reclamation treatment effectively increased the soil pH, microbial density and provided essential plant nutrients for optimum level of plant growth.

Evaluation of plant growth parameters indicates that survivability rate of fruit plants was about 70%. The growth was better in upland as compared to medium land slope. Plant growth at lower slope was not satisfactory due to high percentage of sand and mine spoils and extreme soil acidity caused by oxidation of iron pyrites[20]. In general, the growth of *Citrus reticulate* and *Pyrus communis* plants was found better than *Prunus napalensis* (Table 3). Re-vegetation through plantation of locally adapted fruit plants and grasses or ferns played an important role in reducing the degradation process by stabilizing soils through development of extensive root systems and also in protecting the soil surface from erosion and allowing accumulation of fine particles[21]. The adaptations of native plant species are more effective because of their efficient vegetative reproduction mechanism and low nutrient requirements under low fertile soils[22]. Grasses and ferns used under reclamation processes acted as a nurse crop for an early vegetation purpose[23].

In the case of lowland rice, it was observed that plants suffered from severe nutrient deficiencies at the beginning of reclamation process. This was mainly due to continuous AMD run-off to the rice field during mining which lowered its soil pH to 4.1. At this pH, transformation of essential plant nutrients was restricted, toxicity of Fe and SO_4 increased, and population of bacteria decreased. Several researchers have reported such lower nutrient content, high Fe and SO_4 and poor plant growth in mine spoils[24–27]. Iron toxicity greatly depresses crop yield[28–31]. Lime application effectively lowers the active concentration of these ions in soil solution by increasing the pH from 4.1 to 5.5. Lime was also effective in neutralizing free sulphates and precipitation of excessive Fe. Other effects of liming were change in mineralization of nitrogen and solubility of applied or native phosphorus (Table 1). At pre-reclamation stage, yield of rice grain was only 860 kg ha^{-1} which increased to 1320 kg ha^{-1} after reclamation (Figure 3).

Surface water all around the area was strongly acidic and contained high concentration of dissolved Fe and SO_4 (Figure 4). Observations from a water stream passing nearby the mined areas were also analysed to check the water quality condition. The pH value of AMD water was in the range of 3.2 to 3.8, Fe varied from 10 to 11.8 mg l^{-1}, while sulphate content ranged from 22.5 to 24.6 mg l^{-1}. The higher value of Fe and SO_4 in the drainage water was due to its continuous leaching in pre-mine spoils. AMD that originate from weathering and leaching of sulphide minerals due to pyrite oxidation (FeS_2) present in coal results in highly acidic pH and heavy metal concentration[32]. Iron and sulphur oxidizing bacteria are known to catalyse these reactions at low pH thereby increasing the rate of reaction by several orders of magnitude[33–35].

The lime application, vegetation and safe disposal of run-off from coal pits during reclamation raised the water pH up to 7.2. Interaction of AMD with lime neutralized the acidity and precipitated iron and other metals from water. Vegetation was found beneficial for reducing the amount of water and atmospheric oxygen entering the mine overburden. Thus, the levels of Fe and SO_4 in drainage water reduced considerably in the tune of 26% and 49% respectively. Channelling of AMD and its prevention from contamination of agricultural fields could save agricultural land and water bodies from further degradation.

Based on the field study and considering the typicality of ground realities of coal mining area, it may be concluded that the study area is inflicted with toxic aqueous discharge of Fe and SO_4 contents from spoiled coal mined lands. Presence of AMD depletes essential plant nutrients in soil and oxygen levels in water. This in turn increases acidity as well as toxicity. Channeling of seepage water for checking AMD contamination of water bodies and crop fields, afforestation with native species, lime and organic matter application in soils were effective in mitigating the toxicity problem. Phytostabilization was found to be the most economical and feasible options under existing social and economic conditions for restoring normal soil fertility and plant growth.

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Diversity and conservation status of mangrove communities in two areas of Mesocaribea biogeographic region

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The study of mangrove communities (*Avicennia germinans*, *Conocarpus erectus*, *Laguncularia racemosa* and *Rhyzophora mangle*) in Central America reveals a total diversity of 121 species included in 7 plant communities, of which 15 are characteristic of mangroves and 31 of flooded areas with less pronounced salinity, while 75 are invasive species belonging to neighbouring communities. Frequent fires in the dry forest have caused intense erosion, leading to the silting of the lake basin. As a result, the first belt of *Rhizophora* vegetation is extremely rare. In contrast, there is a predominance of *Laguncularia* and *Conocarpus* mangrove plants, in addition to a belt of Phragmito Magnocaricetea with a high incidence of *Phragmites australis*, which acts as an indicator of sediment silting due to its shallowness.

Keywords: Biogeographic region, diversity and conservation, mangroves, phytosociology.

MANGROVE communities grow in tropical and subtropical areas between parallel 30°N and 30°S on different continents[1–8]. Mangroves are important for their role in estuarine ecological systems and shoreline protection[9–12]. They provide fish breeding-grounds and act as barriers to erosion and habitat for wildlife[13–15]. However, exploitation of mangroves can affect biodiversity and ecosystem services[16,17]. Mendes and Tsai[18] studied of mangrove swamp sediments in transect from the outermost to the innermost areas of a mangrove swamp in Southeastern Brazil. They sampled three points consisting of the species *Laguncularia racemosa*, *Avicennia shaueriana* and *Rhizophora mangle*, and analysed a variety of physical and chemical parameters that condition the microbial biogeochemistry of the soil. They highlighted the need to preserve mangrove areas from degradation. Studied on the degradation of non-mangrove forests in protected areas (PAs)[19,20] in Latin America revealed that they increased from 0.04% to 0.10% between 2004 and 2009, with a considerable rise in area (ha) altered by serious erosion and the resulting sediment deposit[19,20]. This degradation is caused by the density of the rural population and its proximity to the habitat, and to the decline in funding for PAs, however, it is somewhat offset by protection measures in these threatened areas. We recently highlighted the need to establish conservation measures for two American mangrove forests[4], as they are facing a variety of threats[21]. One of these is particularly the high rate of sediment deposit caused by deforestation of peripheral areas, which is silting mangrove forests, as in the case of several mangrove swamps in Mexico (Laguna de Tres Palos, Acapulco, and Guerrero). The *Rhizophora* sp. habitat is being substituted by that of *L. racemosa*, whose habitat is in turn substituted by *Conocarpus erectus*, owing to reduction in depth of the lake basin, an increased inflow of freshwater, and a decrease in salinity. This horizontal dynamics is accompanied by an increase in the area occupied by *Phragmites australis* and *Typha domingensis*[22,23], species whose optimal development occurs in sites with shallow standing water and low salinity, in contrast to the requirements for mangroves. Typical mangrove species are therefore being replaced by others from outside this type of community. Mangrove communities should therefore be regarded as fragile, as they require a specific depth of water and salinity. Another threat to the mangrove habitat is deforestation by the rural community for use as an energy source. This could be reduced if the per capita income of the population were higher, which would allow them access to other energy sources[24,25].

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