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An alternative for agriculture at Lake Alaotra, Madagascar: organic fertilizer and soil amendment from the invasive water hyacinth (*Eichhornia crassipes*)

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ABSTRACT

In the context of a globally increasing human population coupled with continuous environmental degradation, eco-friendly agricultural innovations are essential to reduce poverty and food insecurity in the world. This is particularly evident in developing countries where nature conservation and agricultural production remain in conflict. We investigated the effectiveness of using a locally free natural resource, the invasive plant species water hyacinth (*Eichhornia crassipes*), as a source for organic fertilizer and soil amendment (composts, green manure and ash) at Lake Alaotra, one of the most important agricultural areas of Madagascar. Five different products were produced under the local conditions of Lake Alaotra. In addition, we conducted a growth experiment with Chinese cabbage (*Brassica rapa* ssp. *chinensis*) to evaluate the effectiveness of the water hyacinth products in comparison to the mineral fertilizer NPK—nitrogen, phosphorous, potassium—and to cow dung. The results of our study show that it was easily possible to produce water hyacinth fertilizer/soil amendment under the remote conditions of Lake Alaotra. In addition, our results show that a higher biomass gain of Chinese cabbage treated with water hyacinth composts was achieved compared to NPK and cow dung. A higher biomass gain was mainly obtained due to an improvement of soil structure after compost addition. Water hyacinth green manure and ash showed low performance. Besides, applying composts was cheaper than buying NPK or cow dung. Our results show that water hyacinth can serve as a fertilizer and soil amendment and could help to improve agriculture at Lake Alaotra.

RÉSUMÉ

Dans un contexte d'accroissement mondial de la population humaine couplé d'une dégradation continue de l'environnement, les innovations agriculturales respectueuses de l'environnement sont essentielles pour réduire la pauvreté et l'insécurité alimentaire mondiale. Cette situation est particulièrement évidente au niveau des pays en voie de développement où la conservation de la nature et la production agricole sont en constant conflit. Nous avons étudié l'efficacité de l'usage d'une ressource naturelle locale, la plante envahissante jacinthe d'eau (*Eichhornia crassipes*) comme source de fertilisant organique (composts, engrais vert et cendre) au niveau du Lac Alaotra, une des plus importantes zones agricoles de Madagascar. Cinq types de fertilisants ont été produits à partir de la jacinthe d'eau selon les conditions locales du Lac Alaotra. De plus, nous avons conduit une expérience avec le chou de chine (*Brassica rapa*, ssp. *chinensis*) pour évaluer les performances des fertilisants de la jacinthe d'eau en comparaison avec les fertilisants locaux NPK (11% d'azote, 22% de phosphore et 16% de potassium) et le fumier de bétail. Nos résultats montrent que la production de fertilisants à partir de la jacinthe d'eau et son usage pour l'amendement du sol sont possibles et faciles à réaliser dans les conditions locales. De plus, un gain de biomasse important a été observé avec les choux traités avec les composts de jacinthe d'eau en comparaison avec le NPK et le fumier de bétail. L'important gain de biomasse est certainement dû à l'amélioration de la structure du sol après l'application du compost. L'engrais vert et les cendres de jacinthe d'eau ont montré cependant de maigres performances. De plus, l'utilisation du compost est moins chère par rapport à celle du NPK et du fumier de bétail. Nos résultats montrent que la jacinthe d'eau peut être appliquée en tant que fertilisant et pour l'amendement du sol, et par conséquent peut contribuer à l'amélioration de l'agriculture au niveau du Lac Alaotra.

INTRODUCTION

Biodiversity conservation and sustainable land use are a particular challenge in developing countries of the Tropics where most of the worlds' biodiversity is concentrated but undergoes detrimental and increasing anthropogenic pressures partly from a rural population mostly living from the agricultural exploitation of natural resources (Myers et al. 2000, Urech et al. 2015, Zähringer et al. 2016, Jones et

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al. 2019). In Madagascar, a high rate of population growth coupled with a dependence on natural resources and land for agriculture represents a central problem for biodiversity conservation. Madagascar, one of the most important biodiversity hotspots and one of the poorest countries in the world (ranked 162 amongst 189 regarding the Human Development Index and with 70,7% of the population living under the poverty line), obtains a quarter of its GDP from agriculture that provides employment for 80% of its population (Eubanks 2012, UNDP 2019).

The Alaotra region is one of the most important agricultural areas of the country and represents the rice granary of the island with 120,000 ha of rice fields producing approximately 300,000 tons per year (Copsey et al. 2009, Penot et al. 2014). Apart from rice cultivation, the Alaotra region is also important for other staple foods, vegetable crops, rent and industrial products and fruit production (Penot 2009). From an ecological point of view, Lake Alaotra represents the biggest freshwater wetland of Madagascar with 20,000 ha of open water surrounded by 23,000 ha of marsh vegetation sheltering several endemic plants and animal species such as the Alaotran gentle lemur (*Hapalemur alaotrensis*), the only primate worldwide that lives in wetlands (Guillera-Arroita et al. 2010). Due to the high demographic pressure and rural poverty coupled with soil degradation and high climatic variation (high fluctuation of rainfalls), the local population at Lake Alaotra depends highly on natural resources for securing their subsistence. The main problem for the local biodiversity is the use of shifting cultivation. On a global level, this land use pattern is declining but it is still widespread throughout Madagascar (Curtis et al. 2018, UNDP 2019). This creates a chronic conflict between conservation and development goals leading to marsh conversion into rice fields and overexploitation of natural resources (Copsey et al. 2009, Waeber et al. 2018).

To solve this complex problem, several agricultural innovations have been attempted in the Alaotra region which mainly focused on rice cultivations (SRI System of Rice Intensification, conservation agriculture, use of special rice varieties) (de Laulanié 1993, Chabierski et al. 2006, Jenn-Treyer et al. 2007, Rasoamanana et al. 2011, Scopel et al. 2013). However, their diffusion failed due to several reasons: technical limitations (water control), expensive labour force, costly seeds, requirement of considerable amounts of mineral fertilizer, general preference for rice varieties with long straw used for feeding livestock, long learning process, and competition with fodder for livestock. The doubling of local fertilizer prices in 2008 due to the credit policy failures has aggravated the general skeptical opinions of local farmers toward agricultural innovations. A significant yield difference to the conventional agriculture cannot be reached without an optimal application of NPK (Penot et al. 2012, 2014). Since 2015, the price of fertilizers dropped again to its pre-2008 value, thereby relaunching their usage in the Alaotra region (pers. comm.).

In comparison to rice cultivation, the improvement of vegetable farming has received less attention in the Alaotra region. One main problem for crop planting in the region are the relatively nutrient poor soils. Farmers regularly use fertilizers which are on the one hand expensive and on the other hand harmful for the environment. Within this study, we propose the use of the water hyacinth (*Eichhornia crassipes*) as a source for organic fertilizer and soil amendment. It is one of the most problematic invasive aquatic plant species covering 53% of the marsh belt fringe, altering water parameters and plant communities at Lake Alaotra (Lammers et al. 2015). In addition, we found out that the livelihood of 81% of the local stakeholders at Lake Alaotra (mainly rice farmers and fishers) are affected by water hyacinth, as the plant clogs waterways, reduces fishing areas and thus fish catches, and invades rice fields during the rainy season (Rakotoarisoa et al. 2015). Globally, belonging to the 10 most troublesome aquatic weeds, the water hyacinth has already been successfully used as compost and green manure in China, Indonesia, India, Malaysia, Bangladesh, Sri Lanka, Thailand, Philippines and in some African countries such as Kenya and Nigeria (Gunnarsson and Petersen 2007, Ndimele 2011, Patel 2012). It has been proved to improve soil structure and soil nutrient contents, and the compost is quickly ready for use within one month (Polprasert et al. 1980, Gunnarsson and Petersen 2007). Despite these advantages, the intensive workload (harvesting of plants, transportation and production of compost) required for its production is often a hindrance for the adoption of water hyacinth compost (Gunnarsson and Petersen 2007). Water hyacinth green manure and ashes represent other alternatives with less workload (Gunnarsson and Petersen 2007).

In Madagascar, to our knowledge no attempts have been made so far at using this plant as a source for organic fertilizer and soil amendment. A recent study of Rakotoarivelo (in press) showed that only 30% of the people living in the Alaotra region are using the plant, and those who do use it nearly only as fodder for pigs. We therefore tested if water hyacinth organic fertilizer and soil amendments could be produced in the poor and remote Alaotra region, and if they can substitute or complement the commonly used fertilizers. As a first attempt we decided to focus our study on small scale agriculture and vegetable farming and not on rice production. In the region, three fertilizers are commonly used: the complex mineral fertilizer NPK (Nitrogen-Phosphorus-Potassium), cow dung and urea. Urea is mostly used in rice fields. NPK and cow dung are more commonly used in vegetable farming. NPK is known as one of the best agricultural intensification fertilizers in the region. Despite the doubling of prices in 2008 (Penot et al. 2012), we have observed that NPK is still widely used for vegetable farming. Cow dung is also widely used, although it is very expensive as only few cattle are present in the region. Within this research, we evaluated five different methods of producing organic fertilizer and soil amendment based on water hyacinth (aerobic, anaerobic and pit compost, ash and green manure). In order to identify which water hyacinth product is best suited to replace or complement commonly used fertilizers, we conducted a growth experiment with Chinese cabbage (*Brassica rapa* ssp. *chinensis*), a fast growing and commonly used vegetable in the region.

MATERIALS AND METHODS

STUDY AREA. The research was conducted in the Alaotra region at the end of the rainy season (March-April) 2014. The regional climate is characterized by two seasons: a rainy season from December to April and a dry season from May to November. Annual precipitation ranges from 1092 to 1200 mm. Mean monthly temperatures vary from 11.0 °C in July to 28.4 °C in January (Ferry et al. 2009). The production of water hyacinth organic fertilizer and soil amendment (composts, green manure and ashes) took place in the village of Andreba Gara. The village has a population of approximately 4830 inhabitants, 70% of whom are under 17 years old. Fishing and agriculture are the main sources of income (head of Andreba Gara village, pers. comm.) and daily salaries range from 2.5 US$ to 5 US$ (Rakotoarisoa et al. 2015). Besides the low standards of living, the infrastructure of the region is also weak: there is no permanent electricity and the roads connecting this area to the outside world are few and in bad condition.

SOIL CONDITIONS OF VEGETABLE FIELDS. In order to assess the physico-chemical properties of the soil used for vegetable farming at Lake Alaotra, soil samples were collected from Andreba Gara (n=2) and two further locations: Anororo (western part of the lake, n=2) and Vohimarina (northern part of the lake, n=2). The samples were collected within vegetable fields located between the village and the lakeshore. Soil moisture (%), pH, macroelement contents (organic carbon (C, %), nitrogen (N, %), plant available phosphorus (P, ppm, Bray II), potassium (K, méq/100g), microelement contents (calcium (Ca), magnesium (Mg), natrium (Na) (még/100g)) and texture were measured. Soil type identification followed Sponagel et al. 2005. The soil fertility was assessed using Cation Exchange Capacity (CEC) by measuring the amount of colloids in the soil and the CEC of each of these colloids using buffered method with NH_4^+ (at pH=7). All soil analyses were performed at the Laboratory of Pedology (FOFIFA) in Antananarivo, Madagascar.

PRODUCTION OF WATER HYACINTH ORGANIC FERTILIZER AND SOIL AMENDMENT. For all water hyacinth products, fresh plants were collected at the shore of Lake Alaotra and transported with zebu carts into a Camp ("Camp Bandro", a local ecotouristic camp offering a fenced off and undisturbed area). Afterwards, the roots were removed since water hyacinth accumulates heavy metals and pollutants mostly in these organs (Matindi et al. 2014). The preparation of all water hyacinth products was based on the methods described by Lindsey and Hirt (1999). For green manure, shoots were chopped and sundried for one week prior to incorporation into the soil. For ash production, water hyacinth was sun-dried and burnt thereafter. For the composts, fresh water hyacinth was chopped into 2 cm pieces to speed up the decomposition process. The composts were produced under three different conditions: (i) aerobic conditions (after installing branches at the base of the pile), (ii) anaerobic conditions (using plastic sheets to cover the pile) and (iii) in a pit in the ground. For compost preparation a sequence of three layers was used: cow dung and soil to supply micro-organism for decomposition (5 cm), chopped water hyacinth (20 cm) and mango (*Mangifera indica* L.) leaves to increase nitrogen and the amount of compost in general (5 cm). The layered pile was then watered and layering repeated until the pile was up to 1.5 m. Subsequently, composts were watered every two days and turned onto new bases every two weeks until composting had turned the substrates into a crumbly dark mass after one month (Polprasert et al. 1980).

GROWTH EXPERIMENTS WITH CHINESE CABBAGE. In order to test which water hyacinth product was most efficient in enhancing plant growth and to what degree water hyacinth substrates can potentially replace or supplement commonly used fertilizer, we conducted a growth experiment with Chinese cabbage (*Brassica rapa* ssp. *chinensis*). Chinese cabbage is a common vegetable in the region and particularly suitable as a test crop given its fast growth. Cabbage plants were raised from seeds in a nursery for 18 days before transplantation into experimental pots. Local soil was used in order to simulate the soil conditions under which farmers cultivate crops in the region (Figure 1).

The growth experiment consisted of eight treatments with 12 repetitions per treatment : (i) a control (4,5 kg of local soil per pot),

Figure 1. Location of the Alaotra region, the three localities where soil samples were collected and the village of Andreba Gara where the growth experiment with Chinese cabbage was conducted at the end of the rainy season (March–April 2014).

(ii) aerobic compost of water hyacinth (3 kg soil + 1,5 kg compost), (iii) anaerobic compost of water hyacinth (3 kg soil + 1,5 kg compost), (iv) compost of water hyacinth in a pit (3 kg soil + 1,5 kg compost), (v) green manure of water hyacinth (4,5 kg soil + 76 g of fresh water hyacinth pieces), (vi) ash of water hyacinth (4,5 kg soil + 2,54 g ash), (vii) cow dung (3 kg soil + 1,5 kg cow dung) and (viii) NPK (4,5 kg soil + 2,25 g NPK). The amount of fertilizer was based on the mass balance method and followed suggestions by Gajalakshmi and Abbasi (2002). Plants were watered daily with 800 ml lake water (0.04 mg/L NO_2^-; 2.04 mg/L NO_3^-, 1.18 mg/L PO_4^{3-}) (Lammers et al. 2015), as common in the region at 6 am to avoid quick evaporation. The pots were randomly arranged every three days to avoid effects of possible differences in exposure to sunlight. 30 days after cabbage transplanting, all plants were measured, harvested and separated into leaves, stems and roots. To calculate biomass production, all plant parts were first sun dried in the field and later in an oven at 40 °C for four days to constant weight.

LABORATORY ANALYSIS. Macronutrient contents (total N, total P and K) were determined for all fertilizers and the soil using photometric methods (DIN EN 16169: 2012-11, determination of Kjeldahl nitrogen for total N; DIN ISO 11263: 1996-12, spectrometric determination of phosphorus soluble in sodium hydrogen carbonate solution for total P; and JIS K 0809: 2008-07-20, for total potassium). In addition, pH measurements were performed for all treatments (1:2 with 25 ml 0.01 $CaCl_2$). Soil texture was determined to assess soil drainage (Sponagel et al. 2005). Even though to our knowledge no heavy metal contamination exists at Lake Alaotra, we could also not exclude its presence. As the water hyacinth can store a large amount of heavy metals in its plant compartments and we wanted to avoid any risk, we analysed concentrations of the most common heavy metals (Pb, Cd, Zn, Cu, Cr and Ni) for the soil and water hyacinth samples (n=36) from different parts of the lake (Andreba Gara, Anororo and Vohimarina) by Atomic Absorption Spectroscopy (DIN EN ISO 11885, Calibration method DIN 32645, NLWKN Hildesheim, Germany).

ECONOMIC ASPECTS. To compare the total use costs of the different fertilizer, the costs of raw materials, labour force and transportation using Zebu carts were investigated by questioning local farmers on real local pricing. We rewarded all services related to the experiment according to the local cost standards. The comparison of raw material and transportation costs of the different fertilizer was based on their common application rate per hectare (Lindsey and Hirt 2000, Gajalakshmi and Abbasi 2002, Gunnarsson and Petersen 2007).

DATA ANALYSIS. The Shapiro-Wilk test revealed non-normal distribution of our data. Therefore, the nonparametric Kruskal-Wallis test and Mann-Whitney U test (with Bonferroni correction) were used to determine statistical differences between the treatments.

RESULTS

SOIL CONDITIONS OF VEGETABLE FIELDS. Three soil types were identified depending on the sampling location: loamy sand in Anororo, sandy loam in Vohimarina and sandy clay loam in Andreba (Table 1). Soil moisture varied from 7.9% to 36.9% and decreased with increasing sand content. Generally, soils were acidic (pH 3.4 to 5.4). Nutrient concentrations were low in Anororo compared with those of Andreba and Vohimarina. Except for C and N contents, soil samples from Andreba contained higher nutrient concentrations compared with samples from Vohimarina. In contrast, the CEC was highest for soil in Vohimarina compared with the soils from Andreba and Anororo.

PRODUCTION AND PERFORMANCE OF WATER HYACINTH PRODUCTS. All water hyacinth products could be easily produced under the local conditions at Lake Alaotra. Water hyacinth compost was ready after 30 days. Our results also demonstrate that especially water hyacinth compost was more beneficial for plant growth than commonly used fertilisers as we recorded the highest biomass production of Chinese cabbage in treatments with compost (Figure 2). However, no significant difference occurred between the three compost types. Second highest biomass production was reached in treatments with NPK. Plants that were fertilized with green manure, ash and cow dung showed a very low biomass production. Plants grown with composts (especially with aerobic compost) exhibited better growth (thick, large, numerous and heavy leaves) whereas the remaining treatments (especially when grown with cow dung and ash) displayed poor growth (thin, small, few and light leaves). Plants in the control treatment (plain soil) showed strong signs of water stress, e.g. wilted leaves.

Table 1. Physico-chemical properties of soils at three locations around Lake Alaotra, north-eastern Madagascar. (Data show means of two samples at each site)

	Vohimarina	Anororo	Andreba
Clay (%)	15.0	11.0	23.0
Silt (%)	15.0	3.0	25.0
Sand (%)	71.0	87.0	53.0
Type of soils	Sandy loam	Loamy sand	Sandy clay loam
Humidity (%)	21.9	7.9	36.9
pH	5.45	3.45	4.82
C (%)	8.79	0.42	2.29
N (%)	0.63	0.04	0.21
P (ppm)	10.9	3.3	26.9
Ca (meq/100g)	6.0	2.2	12.0
Mg	3.50	1.50	9.60
K	0.24	0.05	2.18
Na	0.87	0.65	3.39
CEC	80.7	15.1	34.0

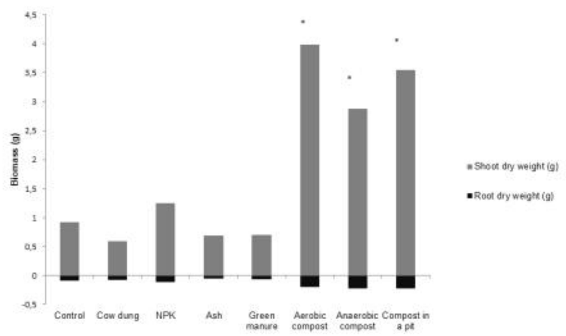

Figure 2. Means of shoot biomass and root biomass for Chinese cabbage grown with water hyacinth and locally used fertilizer. (Asterisks show significant mean difference at $p < 0.05$ using the Kruskal-Wallis test)

NUTRIENT CONCENTRATIONS AND PARAMETERS OF SOIL AND FERTILIZER USED FOR THE GROWTH EXPERIMENT. Macronutrient analyses revealed that the soil used for the experiment was very poor in nutrients (Table 2). Additionally, soil texture analyses showed a high clay content which classifies the soil as weakly sandy (45% <clay< 65%, 0% <silt< 15%, 0% <sand< 10%). Symptoms of water stress were noticed for all treatments except for the pots treated with composts. The pH of the soil (control) and the composts were near neutral with a mean value of 6.57, whereas it was higher (slightly alkaline) for cow dung, green manure and ash (mean 7.8). NPK showed a strongly acidic pH (mean 4.8). Regarding the macronutrient contents, NPK had the highest concentration of total N and total P. K content was highest for the ash. Aerobic compost had higher macronutrient concentrations than pit and anaerobic composts. Green manure had lower macronutrient concentrations than composts but higher ones than cow dung.

ECONOMICAL ASPECTS. The results show that independently from the crops, a higher amount of compost and cow dung would be needed per hectare when compared with green manure, ash and NPK (Table 3). Based on the application rate for one hectare of field, cow dung was the most expensive fertilizer (100 US$ per hectare), followed by NPK (67 US$ per hectare) and compost (20 US$ per hectare) when regarding the raw materials only. Around 2 tons of cow dung are needed to produce 10 tons of compost while the mango leaves can be collected for free. Green manure and ash were made exclusively out of water hyacinth which reduces the costs to transportation costs only. Local farmers said they would collect the raw materials (mango leaves and water hyacinth) themselves without hiring labour force. However, in case they have to hire people, collecting 10 tons of water hyacinth needs in total 3 whole days and 3 men (1.5 US$ per person per day). Collecting mango leaves near the village would take only half a day and could be performed by family members. Transportation cost in the Alaotra region is estimated at approximately 3.2 US$ per ton. The cost allocated to the transportation of each fertilizer type de-

Table 2. Comparison of macronutrient concentrations and pH of the different fertilizer used for the growth experiment with Chinese cabbage at Lake Alaotra, north-eastern Madagascar. (Data show means of two samples per treatment. For soil values see Table 1)

Treatments	N (%)	P (%)	K (%)	pH
Cow dung	0.35	0.09	0.21	7.93
NPK	22.00	4.84	11.62	4.80
Ash	0.00	0.00	23.24	7.92
Green manure	1.29	1.78	1.85	7.80
Aerobic compost	1.99	2.95	2.51	6.26
Anaerobic compost	1.53	1.85	2.34	6.90
Compost in a pit	1.79	2.57	2.36	6.56

Table 3. Application rate and costs of the different fertilizers used for the growth experiment with Chinese cabbage at Lake Alaotra. (*Retrieved from Lindsey and Hirt 2000, Gajalakshmi and Abbasi 2002, Gunnarsson and Petersen 2007)

Type of fertilizer	Application per hectare* (tons)	Costs per hectare (US$)			
		Raw material	Labor	Transportation	Total
NPK	0.1	67.0	0.0	0.3	67.3
Cow dung	10.0	100.0	13.5	32.0	145.5
Green manure	3.0	0.0	4.5	10.0	14.5
Compost	10.0	20.0	13.5	32.0	65.5
Ash	2.0	0.0	4.0	7.0	11.0

pends thus on their respective application rate per hectare. In general, total costs were higher for cow dung, similar for NPK and compost (if farmers had to hire labor force for collecting raw materials) and lower for green manure and ash (Table 3).

HEAVY METAL CONCENTRATIONS. Our results show that water hyacinth contained far less heavy metals than the maximum safe values (Amlinger 2004) regarding compost quality standards (Table 4). As the heavy metal concentrations were very low, no further analysis was made with the fertilizer made from the plant material. Therefore, eventual higher heavy metal contents in water hyacinth compost would come from the local soil but not from the plant.

DISCUSSION

This study demonstrated that it is possible to produce different water hyacinth fertilizer under the local conditions encountered in the Alaotra region (i.e. no electricity, no high technology machine and no infrastructure). Further, the results of the growth experiment with Chinese cabbage displayed higher biomass gain of treatments with water hyacinth compost compared to the other water hyacinth products (green manure and ash) and locally used fertilizer (NPK and cow dung). Therefore, it can be concluded that water hyacinth compost is suitable for improving vegetable field soil structure and fertility and further has the potential to substitute or complement NPK and cow dung in the Alaotra region.

VEGETABLE FIELDS IN THE ALAOTRA REGION: PROBLEMS AND CONTRIBUTION OF WATER HYACINTH FERTILIZER. According to our results, vegetable soils in the Alaotra region show signs of degradation. Generally, the observed soil texture and acidity might affect the soil fertility and plant nutrients availability negatively: the high proportion of sand and the low pH of the soil in Anororo reduced the soil water holding capacity (soil humidity). Additionally, the low pH (3.45) could explain the low amount of soil nutrients fixed by humus and clay. Effectively, the low organic carbon content (0.42%) might reflect the low humus content and the low proportion of clay (11%) might be mainly formed with 1:1-type silicate clays (having less negative charges) common in weathered and acidic soil in the Tropics (Brady and Weil 2008). Another sign of degradation is also the very low amount of plant available phosphorus within soils. In conclusion, the low humus and clay contents could explain the low CEC value and therefore the lower fertility of soil in Anororo. The CEC (80.7) in Vohimarina is far higher than the total nutrient contents measured (Ca, Mg, K and Na). Since buffered methods were used to determine CEC and that pH of native soil (5.45) is lower than buffer solution pH (7), the higher value of CEC in Vohimarina must mainly come from the higher amount of pH-dependent negative charges likely associated predominantly with humus, here reflected by the higher organic carbon content (Brady and Weil, 2008). In Andreba, the value of CEC is closer to the amount of total nutrient contents. This reflects a lower amount of pH-depending negative charges (compared to Vohimarina) which could be due to a lower humus content reflected by the lower organic carbon content.

Management alternatives are suggested depending on the state of degradation of vegetable fields within the three villages (Table 5). Due to its high content in sand particles (87%), the soil in Anororo requires several treatments before being suitable for agriculture. First, clay should be added to the soil to enhance its nutrient and water retention capacity (Noble et al. 2004). Afterwards, the nutrient cycle could be closed by applying water hyacinth compost and chemical fertilizer, reducing tillage, using leguminous plants for catching atmospheric N and retaining crop residues (Bell and Seng 2007). For the soil in Andreba Gara, revegetation of the hillsides should become a priority to reduce soil erosion and embankment of fields downstream while the joint use of chemical fertilizer and water hyacinth compost could supply nutrients and improve soil structure. Due to its relatively high content of sand (71%), clay application might be needed for the soil in Vohimarina. Depending on the case, water hyacinth compost could be applied there to improve soil structure and fertility.

RELEVANCE AND IMPLEMENTATION OF WATER HYACINTH COMPOST USE AT LAKE ALAOTRA. Although green manure and ash generally seem more attractive considering their low degree of investment and complexity, they showed poor performances in Chinese cabbage yields compared to water hyacinth compost. Promoting water hyacinth compost is a practical and efficient method to improve soil structure and nutrient contents while at once reducing the harmful ecological and socioeconomic impacts of this invasive plant in the Alaotra region. In contrast to NPK, compost can retain nutrients in the soil, avoiding therefore the further eutrophication of Lake Alaotra due to nutrients entry by runoff (Polprasert et al. 1980; Lammers et al. 2015). Besides, it can increase soil resistance to erosion, suppress plant diseases and improve soil fertility and its water holding capacity (Eklund 1996, Gunnarsson and Petersen 2007). Further, the low concentration of heavy metals in water hyacinth supports its suitability as source of fertilizer in the region.

Taking into account the different barriers hindering agricultural innovations at Lake Alaotra, in general low cost, simple, low time consuming and cost-effective innovations seem to hold better chances to be accepted and adopted by farmers (Penot et al. 2014). The water hyacinth compost fits to these criteria: At Lake Alaotra, the invasive water hyacinth is an abundant and free-floating plant that can be directly processed into compost next to the lakeshore. Gunnarsson and Petersen (2007) considered the use of water hyacinth as compost as the best way for reducing costs since the labor can be undertaken during the rainy season next to the area where plants are harvested,reducing transportation efforts. Besides, the additional inputs (cow dung and mango leaves) needed for composting were locally available and the whole process did not require much time or any sophisticated equipment

Table 4. Means of heavy metal concentrations in water hyacinth (n=23) and local soil (n=23) at Lake Alaotra. (*Retrieved from Amlinger (2004))

Heavy metal (mg/Kg)	Water hyacinth	Local soil	Compost quality standards*
Cd	< 0,001	< 0,001	1.0
Ni	< 5	80.0	60.0
Cr	< 5	147.0	70.0
Pb	< 5	25.5	120.0
Cu	17.0	125.0	150.0
Zn	26.0	170.0	500.0

Table 5. Nature of soil, ecosystem degradation and soil restoration alternatives for the three villages around Lake Alaotra.

	Anororo	Andreba Gara	Vohimarina
Soil type	Loamy sand	Sandy clay loam	Sandy loam
Ecosystem degradation	High	Middle	Low
Restoration measures	Clay application; Water hyacinth compost; chemical fertilizer; leguminous plants; reducing tillage; retaining crop residues	Water hyacinth compost; chemical fertilizer	Clay application; Water hyacinth compost; retaining crop residues

or technology. Further, the results of this study displayed that applying compost was cheaper than using NPK (if farmers collect raw materials themselves) and cow dung. However, using NPK shows practical advantages since it requires no production costs and can be applied immediately without any treatment. The relatively short time required for the compost maturation (1 month vs up to 3 to 6 months for other compost types) could be an important driver for its local acceptance. The urgency of providing for the immediate needs of families induces general short-term time horizons within farmers in poor countries (Pannell et al. 2014). However, since even the relatively short time required for the compost maturation could be perceived as a long term investment for poor farmers, assisting local farmers who are interested in the production and marketing of water hyacinth compost on a larger scale could present an additional option to decrease the negative effects of this invasive plant on the biodiversity and livelihoods at Lake Alaotra (Rouse et al. 2008). Thus, other farmers could directly purchase water hyacinth compost without spending time producing it. This would also offer new economic perspectives for people specializing in compost production. Finally, including water hyacinth composts in conservation agriculture at Lake Alaotra could relaunch its diffusion. The moderate increase of income and yield by conservation agriculture could be improved by a reasonable intensification consisting of combining water hyacinth compost with chemical fertilizer (Urea, NPK) leading to a significant and sustainable improvement in productivity (Penot et al. 2014). Considering its simplicity, low costs, high production speed and productivity, water hyacinth compost would likely be attractive to local farmers at Lake Alaotra.

So far it is difficult to assess how successful water hyacinth use as source of fertilizer has been on a global scale since the studies are based on results of experiments and recommendations. Practically no data about real diffusion are available. This might be linked to the intensive labor required for transportation, making a large scale application of water hyacinth compost very difficult (Gunnarsson and Petersen 2007).

The success of the diffusion of water hyacinth fertilizer will require efforts of capacity building, creation of demonstration plots and interested farmer groups to share, exchange and spread knowledge and information (Wall 2007). On a large scale, the success of the implementation of agricultural innovations such as water hyacinth compost must include not only knowledge transfer but also taking into account the economic, social and institutional settings characterizing the targeted region (Klerkx et al. 2012). This implies especially maintained financial support of local farmers. This is important for the Alaotra region where poor farmers constantly struggle with land availability and demographic pressures, market instabilities and environmental problems.

CENTRAL FACTORS INFLUENCING CHINESE CABBAGE GROWTH WITHIN THE GROWTH EXPERIMENT. Photosynthetic efficiency affects plant growth and is influenced by radiation use efficiency, water use efficiency and nitrogen use efficiency (Badger 2013). In our case, the first two parameters (light and water supply) were controlled, allowing over a first phase the use of N supply as central factors for explaining the results. Knops and Reinhart (2000) found that the increase of N input generally implies an increase of plant biomass. This was not the case for this study. On the one hand, high N content of NPK (which is directly available for cabbage) did not lead to higher biomass gain. On the other hand, higher biomass gains were measured with plants treated with water hyacinth composts having lower N contents than NPK. These observations could allow deducing that the biomass production of Chinese cabbage might not have been influenced by the macronutrient contents of the different fertilizers. Instead, the improvement of soil structure by water hyacinth composts might offer a better explanation for high biomass gain of Chinese cabbage treated with them.

Clay-rich soils have poor aeration and drainage, retaining tightly water and hindering water supply for the plants (Leeper and Uren 1993). In our study, positive influences of the water hyacinth composts on the structure of the local clay-rich soil used for the growth experiment were shown by the better water percolation after watering the Chinese cabbage. This infers that the soil structure improvement by the composts might provide a better explanation for the increased biomass production than the macronutrient contents of the fertilizer. Effectively, composts could improve soil structure and nutrient availability (Carpenter-Boggs et al. 2000). Additionally, the significantly higher root biomass of Chinese cabbage treated with composts might be a sign of a better soil structure within these treatments, which in turn fosters a better access to water and nutrients for the plants. Therefore, the unexpected low agronomic performances of the remaining tested fertilizers might be the result of an unreduced water stress experienced by Chinese cabbage due to the clay-rich soil composition that might have subsequently reduced water percolation and plant nutrient uptake. The observed withered leaves of Chinese cabbage might have been a sign of water stress. The strong acidic pH of NPK (4.8) is undoubtedly harmful for the soil since it hinders soil microbial activities (Singh and Kalamdhad 2013).

CONCLUSION

Efforts concentrated on poverty and food insecurity alleviation for rural populations in developing countries is likely to be the best strategy to keep natural ecosystems safe. In poor countries, such as Madagascar, food production will always have the priority over nature conservation in a system where no alternatives are present. In this study, we evaluated the efficiency of using the invasive water hyacinth as an alternative source of fertilizer for vegetable fields in the Alaotra region in Madagascar. The results of the growth experiment using Chinese cabbage showed higher biomass production by water hyacinth composts when compared to NPK and cow dung. Thus, water hyacinth composts are suitable and can substitute NPK and cow dung for vegetable farming in the Alaotra region. Besides, the overall production and transportation costs for compost were cheaper than NPK and cow dung. Further, no health risks were detected considering heavy metal concentrations within water hyacinth at Lake Alaotra. Future application of water hyacinth composts should first target poor farmers making subsistence agriculture on small fields. Demonstration plots are here needed to check and confirm the results under real farming life conditions before upscaling, especially for estimating the real duration of required workload, which might be the main barrier for the adoption of water hyacinth as source of organic fertilizer. Over the long term, water hyacinth fertilizer could be applied to rice cultivation at Lake Alaotra. Most of all, the agricultural past of the Alaotra, especially the lessons learnt from several failures in disseminating agricultural innovations, should be considered in future implementation attempts. Finally, a holistic approach entailing technical, social, economic, environmental and institutional aspects is recommended to promote the use of water hyacinth compost at

Lake Alaotra where food production and nature conservation are competing for the same land.

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