# Worldwide Invasion Pathways of the South American *Eichhornia crassipes*

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## Abstract

**The water hyacinth *Eichhornia crassipes* (Mart.) Solms is one of the 100 world's worst invaders. Native to tropical freshwaters of tropical South America, with a putative origin in the Amazon basin and the Pantanal of western Brazil, the water hyacinth is nowadays distributed worldwide. In tropical regions, *E. crassipes* escaped into local environments and spread out into the freshwaters proliferating aggressively mainly by means of vegetative reproduction. Due to its ability to double its biomass within only 12 days, it rapidly covers whole waterbodies and destroys ecosystems. Several independent anthropogenic introductions into the tropics worldwide took place. Given the environmental and economical dangers related to the expansion of *E. crassipes,* the role of botanical gardens as initiators of invasions and of other anthropogenic migration factors, such as missionaries and colonists in the past as well as tourists, nurseries, private and commercial internet trade must be taken seriously. The dangers linked to the expansion of this highly aggressive species with high growth rates and no local enemies should not be underestimated, especially in view of a further increase of its expansion and favourable growth conditions in formerly non-suited habitats as a consequence of climatic changes.**

## INTRODUCTION

*Eichhornia crassipes* (Mart.) Solms, the common water hyacinth (Fig. 1A) is one of the worst weeds in the world. Because of its beautiful flowers it has been exorted to decorate ponds and occasionally escaped into local environments where it reproduced incredibly fast. Some cite the species as the worst aquatic weed worldwide (Oberholzer, 2002). Its native range is the Amazon basin in South America, but nowadays it is introduced and even cultivated in more than 50 countries on five continents (Fig. 1B; Gopal, 1987).

The proliferation of water hyacinth in its exotic range is determined largely by two factors: nutrient supply and the absence of natural enemies of the weeds. They do not tolerate brackish water (Holm et al., 1977) and salinity can limit or modify their distribution. For example, water hyacinth, which accumulates in the coastal lagoons of West Africa during the wet season, is reduced in those areas which become saline during the dry season. Elevations are not important: they occur near sea level as well as up to an elevation of 1.600 m or higher (Smith, 1979).

The spread of this invasive species is closely linked to biologists, botanists, and travelers who carried *E. crassipes* to Africa, Asia, and the other continents between the 16$^{th}$ and the 20$^{th}$ centuries. These initial populations grew so fast and became so thick that they choke lakes and rivers (Fig. 2). Because of their extremely fast reproduction and high biomass production (Madsen, 1993), and because of their aggressive spread all over the world this species is of high interest not merely to biologists but also for tasks of environmental conservation and local economy.

## MATERIALS AND METHODS

### Productivity and Biomass of *Eichhornia Crassipes*

*Eichhornia crassipes* is an aquatic free floating species in freshwater lakes, marshes, canals, and slow-moving streams whose growth is favored by nutrient rich water. *E. crassipes* reproduces mainly vegetatively, by forming daughter rosettes, especially when warm and shallow water or saturated soils for seed germination are missing (Barrett, 1980). *E. crassipes* dominates in the northern part of South America. It can float freely because of the spongy tissue in its leaves (Fig. 2).

An acre of floating mats of water hyacinth can weigh more than 200 tons, and mats may double their size in as little as 6-18 days (Lindsey and Hirt, 1999).The exact time of biomass doubling depends on location and time of year. As a free-floating plant, all its nutrients come from the water column (Sculthorpe, 1985) and thus they depend on nutrient-rich environments.

In fact, Sale et al. (1985) found that *E. crassipes* has extremely high relative growth rates and short doubling times with respect to both dry weight and leaf area in uncrowded conditions. When plants become competitive with their neighbours, these growth rates drop, biomass per unit water surface area increases, and the plants proceed to further developmental phases. However, while the plants could float into open water they remained in a vigorous colonizing phase with a high rate of new leaf production and many active meristems. Throughout this time they maintained high and constant relative growth rates and a low biomass per unit water surface area.

### What is the Problem?

Water hyacinth is one of the worst weeds in the world (Vietmayer, 1975; Holm et al., 1977). The Invasive Species Specialist Group (ISSG) has nominated this species as among 100 of the "World's Worst" invaders as it is introduced in most warm countries on our planet, mainly in non-flowing water bodies. Its fast growth and extremely high biomass productivity makes a dangerous pest of this invasive plant (Fig. 2). It has therefore the role of "ecosystem engineer" or of an invasive habitat modifier.

Water hyacinth reproduces vegetatively by means of stolons which are readily distributed by water currents, wind, boats and rafts. *E. crassipes* forms large, free-floating, monospecific mats that compete with other aquatic species for light, nutrients and oxygen. Mats degrade water quality by blocking the air-water interface and greatly reduce dissolved oxygen levels and light thus significantly altering invertebrate and vertebrate communities, and eliminating underwater animals such as fish (Penfound and Earle, 1948). As biomass from mats decomposes, organic input to sediments increases dramatically (Gopal, 1987). Fish spawning areas may be reduced and critical waterfowl habitat may be degraded. Water hyacinth greatly reduces biological diversity: mats eliminate native submersed plants by blocking sunlight, alter emerged plant communities by pushing away and crushing them, and also alter animal communities by blocking access to the water and/or eliminating plants that animals depend on for shelter and nesting (Gowanloch, 1944).

Furthermore, water hyacinth may interfere with the use of a water-body for cultural, social or commercial purposes causing substantial economic hardship and putting livelihoods at risk. The mats affect boat traffic, fisheries and energy generation by plugging water turbines, they reduce flow velocity, choke irrigation channels, and provide breeding grounds for disease-carrying insects (Smith, 2002). Its adaptability to little competed ecological conditions makes its eradication virtually impossible and control extremely difficult (Gutierrez et al., 2001). Accumulations of *Eichhornia* on water surfaces are an optimal breeding habitat for hosts of human pathogenes such as malaria (the mosquito *Anopheles* as host for different *Plasmodium* species) and bilharzia (the snail *Biomphalaria* as host of *Schistosomiasis*).

**Control**

Three basic techniques exist for its control; chemical, mechanical, and biological. Chemical control is least favoured owing to the potential damage that herbicides could cause the lake and surrounding agriculture. Herbicidal control of large infestations of water hyacinth growing under favorable conditions has been attempted only rarely (Olaleye and Akinyemiju, 1996) and even when enormous resources have been invested, as in Sudan, has had little effect. However, this method has been successful for controlling small infestations.

Mechanical removal has been attempted but is largely ineffective. In the Orinoco Delta in Venezuela a simple system of boles has been installed which open with the outflowing water at low tide and close with the inflowing water at high tide, thus transporting the *Eichhornia* mats towards the ocean in a sort of sluice system (Fig. 3A). In other conditions mechanical control is linked to high costs due to expensive machinery and manpower and thus is less efficient.

Biological control is therefore the most favoured method of control. In 1995 the Kenya Agricultural Research Institute (KARI) released *Neochetina eichhorniae* (mottled water hyacinth weevil) a native tropical American bug that feeds exclusively on water hyacinth. A mass rearing programme was also begun which has now released at least 142,000 weevils at 30 sites along the Lake Victoria shoreline (LVEMP, 2000). In South Africa, a program to introduce one of its native predators, the grasshopper *Cornops aquaticum* as a control agent to combat *Eichhornia* growth (Oberholzer and Hill, 2001; Adis and Junk, 2003), was stopped through the activity of Prof. Joachim Adis and his team. Since *Cornops* does not essentially reduce the biomass of *Eichhornia crassipes*, it was not clear whether the introduction of a potentially dangerous grasshopper would have been effective, or if side effects – e.g. the introduced arthropods becoming a plague themselves – would have caused even more trouble.

**Possible Usage of Water Hyacinth**

While the majority of scientists see water hyacinth as a noxious weed posing an ecological disaster on pristine aquatic environments, many locals have taken water hyacinth as an economic opportunity. In most invaded countries it is being used for forage, as compost and fertilizer, for the production of briquettes, cellulase and paper, fiber board and rope, as a source of methane gas, or for the production of furniture (Fig. 3B). Nevertheless, the idea to use the enormous netto productivity for human purposes did not yield solutions to the problems posed by the invader (Kikuchi et al., 1997). An interesting use of *Eichhornia crassipes* is water treatment and phytoremediation: it is known to resist and survive high concentrations of heavy metals (zinc, copper, mercury and others), which are a major problem in wastewater.

**Invasion Pathways Around the World**

After having been described scientifically in 1823 – the genus name honours the Prussian minister Johann Albert Friedrich Eichhorn (1779-1856) – *Eichhornia crassipes* was transferred to Europe by the early 18th century (Kitunda, 2006). *Eichhornia* conquered the worldwide tropics by diverse different campaigns, mainly starting from Europe in 1880, supported by interested botanists.

In Asia, *Eichhornia* reached a botanic garden in Java because of its attractive flowers (http://www.tu-darmstadt.de/fb/bio/bot/eichhornia/). From there – thrown into a river – it spread rapidly over tropical Asia. By 1905 it could be found all over the continent. According to other reports, *Eichhornia* came to Europe in 1880 and from here it reached the Indonesian Island Java in 1884. In China, water hyacinth was distributed widely into almost all provinces for animal food in the 1950's and 1960's. After artificial transplanting, mass rearing and breeding, water hyacinth was distributed to further areas in the 1970's (Jianqing et al., 2001).

For the African continent, several introductions at different places and time points within the $16^{th}$ and $20^{th}$ century are described (summarized by Kitunda, 2006). One of the first introduction events is reported from Egypt in the late 1790's by the French botanist Alire Raffeneau-Delile (specified below). Whereas in Lake Victoria, where it is one of the major threats to the local biodiversity today, it was not reported until 1989 although it is believed to have been present since at least the early 80's (Twongo and Balirwa, 1995). The problems associated with water hyacinth however did not become apparent in Lake Victoria until the early 90's. By 1995 90% of the Ugandan coastline was covered by the plant). Kitunda reports in his summary that "between 1880 and 1980, water hyacinth appeared as an ecological nuisance in many parts of Africa. It caused a popular crisis in South Africa in the 1910's, Madagascar in the 1920's, Tanzania, Uganda and Kenya in the 1930's through the 1970's. In the 1980's and 1990's, water hyacinth bloomed heavily on Lake Victoria, the Nile, the Congo and almost all watercourses of Africa."

Water hyacinth reached the North American continent in 1884. It is believed to have been introduced into the U.S. in this year at an exposition in New Orleans (IFAS, 1998); within 70 years of reaching Florida, the plant covered 126,000 acres of waterways.

In the 1890's the water hyacinth was brought also to Australia as an ornamental plant for ponds (Burton, 2005). In New South Wales it was recorded for the first time in 1895. Already in 1897, the government botanist Maiden noted a rapid spread of *Eichhornia* in all the ponds in the Royal Botanic Gardens in Sydney and "warned that the plant should be kept away from the northern rivers where it 'may very rapidly become a serious pest..." (Burton, 2005). In spite of the advanced warning by the early 1900's it had spread along the north-eastern regions of New South Wales and the east coast of Queensland as well. In 1976 a major infestation covering 7000 hectares, threatening the Murray-Darling system has been recorded being under control now but requiring annual monitoring and maintenance (Burton, 2005).

Today, the distribution of *Eichhornia* is worldwide. A fast and easy overview of the present distribution of the invasive *Eichhornia* is given by the Global Invasive Species Database of the Invasive Species Specialist Group (ISSG) of the IUCN Species Survival Commission. Though this weed is reported to exhibit frost sensitivity, individuals of *Eichhornia* happened to survive even in temperate Germany (Lösch, pers. comm.) where the small river Erft near Düsseldorf has a minimum winter temperature of 10°C due to a coal-fired power station in the region. So far, this is the northernmost report of occurrence of *E. crassipes*.

**Biota Transfer Among Continents: Three Main Institutions Are Responsible**

A good overview of the main institutions which were instrumental to the transfer of biota between continents before the 20$^{th}$ century is given by Kitunda (2006): "First, Christian missionaries, particularly Catholic missionaries, brought to Africa their long-standing tradition of collecting and carrying with them exotic plants and growing them in mission stations that they established in foreign lands. Jesuits, Capuchin, and the White Fathers missionaries are said to have introduced water hyacinth in the offshore islands of Africa from the early 17$^{th}$ century onward. Around 1900 the White Fathers introduced water hyacinth in Rwanda, at the headwaters of the Kagera River, which drains into Lake Victoria and exits the lake as the Nile River. The second factor in the spread of water hyacinth in Africa was a network of museums which emerged in the 19$^{th}$ century. Early samples of water hyacinth are still available in museum herbaria in Africa. The plants escaped from these herbaria to the open water in the 20$^{th}$ century, but mere escape was not enough to allow the plant to proliferate. Another set of factors – change in hydrology and chemistry of African water courses – promoted the expansion of small amounts of water hyacinth to crisis levels. The third important institution in the transfer of water hyacinth to Africa and Asia was the network of botanic gardens and fish hatcheries that Europeans established in Africa from the middle of the 17$^{th}$ century onwards. Subsequently, navigation activities between various European missionary or botanical stations promoted accidental spread of water hyacinth along the African water courses."

## The Diversity of Worldwide *Eichhornia Crassipes* Populations

Despite its wide range of occurrence and its economical importance, an overarching analysis of *E. crassipes* comprising populations in its native range as well as from introduced regions has not been accomplished on molecular genetic level. Genetic studies exist: Ren et al. (2005) could demonstrate that Chinese populations of *Eichhornia crassipes* show low genetic differentiations probably due to low levels of sexual reproduction. These results based on random amplified polymorphic DNA markers (RAPDs). The worldwide propagation of *E. crassipes* was not analysed until a recent study by Parolin et al. (unpubl.), who analysed patterns of gene flow and genetic structure in its native range and in the invasive populations worldwide. For this to date unpublished study, samples were collected all over the world and molecular analyses were carried out (AFLP and cpRFLPs). The results showed that there were several diverse independent introductions worldwide, confirming worldwide weed reports which postulate different sites and origins of introductions. The samples taken from China and India clustered within different parts of the northern South American populations indicating several introductions of *E. crassipes* from different regions of the North of South America (Brazil and Peru) into the Asian tropics. Individuals from Laos seem to be introduced from different parts of the northern as well as southern populations of South America. The three individuals sampled in Niger showed different origins: one from a Peruvian population and two from the southern cluster of South America (Argentina / Uruguay).

## CONCLUSIONS

Most scientists nowadays consider invasive species to be one of the top two threats to this planet's native plant life – almost as much as habitat loss. Yet invasive plants are still commercially available, and a few of them are wildly popular, like *E. crassipes* for aquaristic purposes. Only in 2006 it was introduced by mistake in Tuscany, probably as a result of the release from aquaria (Lastrucci and Foggi, 2006).

The most important criteria fulfilled by these invasive species are their ability to escape from natural enemies, rapid growth, strong ability to reproduce vegetatively, early maturity and the production of many seeds which are dispersed widely (such as by birds or wind) and germinate quickly, and often also the capacity to produce seeds asexually.

Unfortunately, it is difficult to predict whether new species will become invasive if introduced to other ecosystems. There are a few computer models that offer some guidance on whether or not a new species is likely to become invasive (Marinelli, 2000). Especially in the light of climatic changes, vegetation patterns are changing and many species formerly not invasive in Europe are now spreading favoured by milder climatic conditions – as is the case in *E. crassipes*.

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## Figures

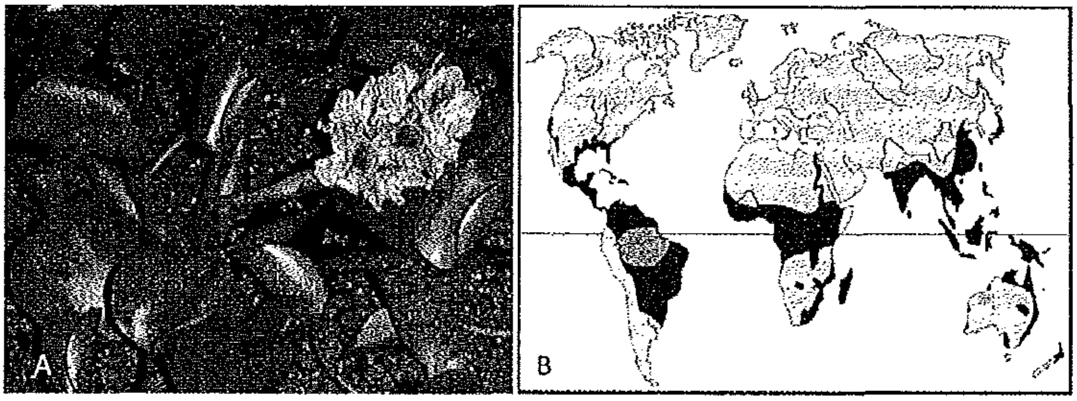


Fig. 1. *Eichhornia crassipes* (A; Photo Parolin, 2008) and (B) its native (light grey) and invasive range (dark grey).

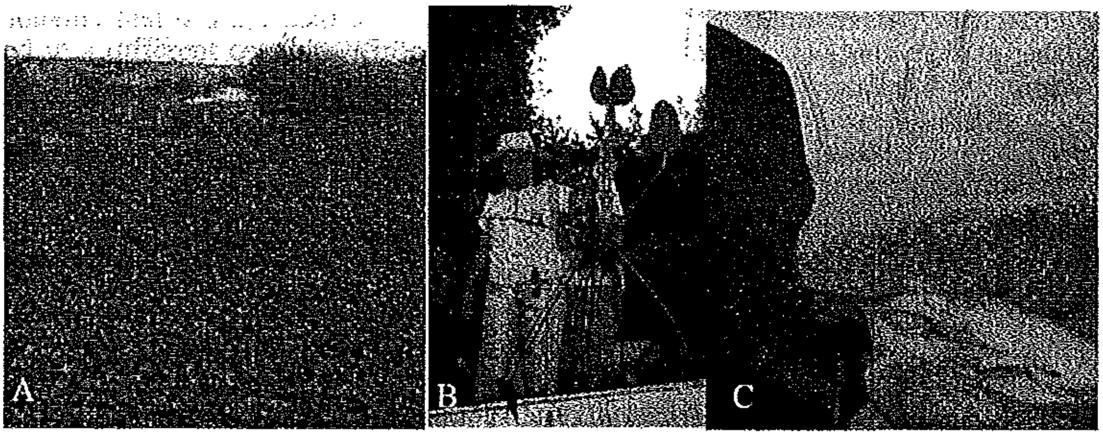


Fig. 2. (A) *E. crassipes* covers huge wetland areas in the Krüger National Park (Photo Parolin, 2009). (B) Single plant of *E. crassipes* in the Pantanal of Brazil, with adventitious roots and vegetative sprouts (Photo Parolin, 2008). (C) Spongy tissue in the leaves of *E. crassipes* which enhances floatation (Photo Parolin, 2008).

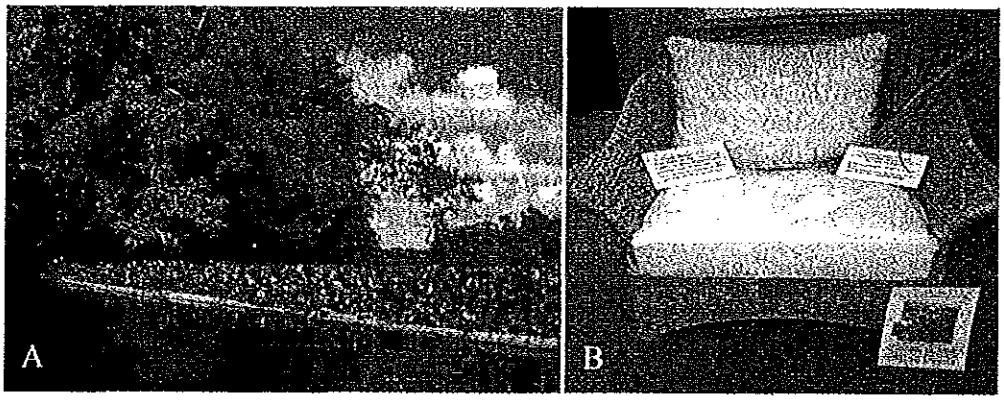

Fig. 3. (A) Orinoco Delta in Venezuela with a sort of sluice system of boles which open with the outflowing water at low tide and close with the inflowing water at high tide, transporting *Eichhornia* mats towards the ocean (Photo Parolin, 1990). (B) Use of *E. crassipes* for the production of furniture (Photo Parolin, 2006, Zukunftszentrum Mensch-Natur-Technik-Wissenschaft, Nieklitz).