INSECTS USED FOR BIOLOGICAL CONTROL OF THE AQUATIC WEED WATER HYACINTH IN PAPUA NEW GUINEA

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ABSTRACT

*Water hyacinth (*Eichhornia crassipes*) was first found in PNG in the early 1960s. By the late 1980s, it had spread to a number of locatioins including the Lower Sepik River, East Sepik Province, where it was expanding rapidly and causing serious problems for the Lower Sepik River communities. An AusAID funded biological control programme, from 1993 to 1998, resulted in four biological control agents, the weevils* Neochetina eichhorniae *and* N. bruchi, *and the pyralid moths* Niphograpta albiguttalis *and* Xubida infusellus *being released. The two weevil species caused significant reductions of the weed in PNG while the moth* X. infusellus *established at one site only with no impact. The second moth* N. albiguttalis *did not become established. We review the biology of each insect, the introductions, release strategies and monitoring for these biological control agents, especially the three that are now part of the PNG biota.*

Keywords: *Biological control;* Eichhornia crassipes*; water hyacinth; Papua New Guinea;* Neochetina eichhorniae; Neochetina bruchi; Niphograpta albiguttalis; Xubida infusellus*; Sepik River.*

INTRODUCTION

Water hyacinth, *Eichhornia crassipes* (Martius) Solms (Pontederiaceae), is among the world's most serious aquatic weeds (Holm, *et al.* 1977). A native of tropical South America, its invasion of rivers and lakes around the world has rendered waterways useless for utilisation by humans and compromised aquatic ecosystems. Large populations of the free-floating weed can create severe hardships and economic difficulties for humans. In a single growing season the weed can impact on riparian communities by disrupting transportation, interfering with hydroelectric schemes, killing fish and promoting diseases. In agricultural areas such as rice paddies, water hyacinth can become a major weed. The weed can clog irrigation pumps and increase water loss through evapo-transpiration. During flooding, water hyacinth can pile up against bridges, culverts, fences, and barriers, thereby blocking water flow and increasing water levels. Impacts caused by water hyacinth are reviewed in Gopal (1987) and Julien *et al.* (1999).

Water hyacinth was first reported in Papua New Guinea (PNG) during 1962 around the mining town of Bulolo (Mitchell 1979). Despite repeated attempts to have early infestations of the weed eradicated by removal (Fig. 1), it persisted and spread to several towns including Lae, Port Moresby, Rabaul and Goroka where it was sold at the local markets (Mitchell 1979; Laup 1987). The water hyacinth invasion seriously affected the livelihoods of thousands of people in the Lower Sepik area and later in the Middle Sepik, after it was introduced from Madang to a village south of the township of Angoram in 1986 (S. Laup, pers. comm.). It spread rapidly and became a very serious aquatic weed on the Sepik floodplain during the five years following its introduction.

Biological control of water hyacinth has been attempted in many countries since it was started in USA in 1961 (Julien & Griffiths 1998; Julien 2001). Much is known about the natural enemies of water hyacinth through the work of various research teams working in the native range of the weed (Bennett 1970; Conway, *et. al.* 1978; DeLoach 1975; DeLoach & Cordo 1978; Sands & Kassulke 1983; Cordo 1999), and current knowledge has been reviewed by Julien (2001). Of the many natural enemies found in the native range, only five insect species and a mite have been deliberately released and established in at least one major region of the exotic range of water hyacinth (Harley & Wright 1984; Julien 2001). A fungus, *Cercospora rodmanii* Conway, was found established in South Africa. It was field collected and redistributed to other areas in South Africa (M.P. Hill, pers. comm.). Three insect species,

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the weevils *Neochetina eichhorniae* Warner and *N. bruchi* Hustache (Coleoptera: Curculionidae), and the moth *Niphograpta albiguttalis* Warren (Lepidoptera: Pyralidae) have been widely utilised (Julien & Griffiths 1998), and particularly the two weevils have helped control the weed in a number of countries (Julien 2001).

Biological control of water hyacinth in PNG began in June 1985 when 500 adults of the weevil *N. eichhorniae,* imported from Australia, were released at a small infestation near Madang (Laup 1987). The weevils became established, increased in numbers and some were collected and redistributed to Bulolo in July 1986, the Sepik River in March 1989, 1991 and 1992, and to the Lae area in 1992 (P. Pandau, unpubl. report). Prior to these releases, all efforts to address the increasing water hyacinth problem promoted eradication by collection and burning (Mitchell 1979; Laup 1987).

In January 1993, a six-year project to manage water hyacinth commenced. It was supported by AusAID and PNG Department of Agriculture and Livestock (DAL). The project objectives were to locate all infestations of water hyacinth in PNG and instigate manual removal or biological control, reduce spread of the weed by raising public awareness, and increase the capabilities of PNG to undertake future biological control work (Julien & Orapa 1999). The biological control aspects of the project included: the mass rearing and release of *N. eichhorniae*, the collection and redistribution from established field populations, and the introduction, mass rearing and releasing of additional biological control agents. New introductions of *N. bruchi* and the moths *N. albiguttalis* and *Xubida infusellus* Walker (Lepidoptera: Pyralidae) were made between 1993 and 1997 from Australia, where they had been tested and released earlier. Host-specificity testing was conducted in Australia for the leaf-sucking bug *Eccritotarsus catarinensis* (Carvalho) (Hemiptera: Miridae) to assess its biosafety for release in Australia and PNG (Stanley & Julien 1999). It was rejected for release in both countries.

This paper reviews surveys for water hyacinth in PNG and the biology of each of the four insects biological control agents released in PNG on water hyacinth. It also outlines the rearing and releasing strategies for those agents.

Biology and Ecology of Agents

N. bruchi and N. eichhorniae

The two weevils *N. bruchi* and *N. eichhorniae* have been the most widely used biological control agents against water hyacinth (Julien & Griffiths 1998). Their host-specificity has been studied in twelve countries involving 274 plant species in 77 families. In the 32 countries where they have been released and have become established (Julien 2001), no sustained attack on species other than water hyacinth has been observed (Julien *et al.* 1999).

Although *N. bruchi* and *N. eichhorniae* broadly resemble each other, their appearance, life history and behaviour differ in a number of ways. Generally, adults are 4 - 5 mm long and adults of *N. bruchi* are larger than those of *N. eichhorniae*, weighing an average of 4.53 mg compared to 3.49 mg (DeLoach & Cordo 1976). Young adults of *N. bruchi* have a distinctive 'v' shaped pattern on the elytra (wing covers). In *N. eichhorniae* the adults are greyish, lack any pattern on the elytra, and have two parallel tubercles which are longer than those on *N. bruchi.* These tubercles may be of unequal length, and are located closer to the front of the elytra. These differences are illustrated in Julien *et al.* (1999).

Neochetina bruchi prefers high quality plants such as those growing in water bodies replenished regularly with plant nutrients (from sewage, industrial discharge, flooding, agricultural runoff or constant flow that passes nutrients over the roots) (Center 1994; Heard & Winterton 2000). *N. eichhorniae* can tolerate varying foliar nutrient levels. Populations of both species may vary relative to each other temporally and spatially depending on the nutrient quality of the plants on which the populations feed. These adult feeding preferences appear to make the two species complimentary in their attack on water hyacinth over the range of nutritional conditions in which the weed grows.

In both species, the adults are photophobic and nocturnal, feeding preferentially on the soft tissue of unfurled young lamina and upper portions of young petioles. During the day adults move to the base of petioles or remain within the safety of unfurled young leaves, leaf sheaths or among the roots. Center and Wright (1991) found that adults of *N. eichhorniae* are attracted to young leaves by natural plant products that stimulate them to feed, especially at previous sites of injury. The weevils feed by scraping and consuming the epidermal layer leaving characteristic, sub-circular scars, 1 to 2 mm diameter, on the upper surface of laminae and on the upper petioles.

Eggs are small, ovoid, 0.8 mm x 0.6 mm for *N. bruchi* and are slightly smaller and softer for *N. eichhorniae*. They are laid in the aerenchyma tissues in the petioles, singly or in groups by *N. bruchi*, whereas they are usually deposited singly

in the epidermis of young or mature leaves and petioles, particularly at adult feeding sites, by *N. eichhorniae* (DeLoach & Cordo, 1976; Center, 1994). Variable numbers of eggs per female have been reported with totals for highly fecund individuals of between 300 and 900 (Center 1994; Julien *et al.* 1999). Incubation period varies from 7 to 8 days at 30°C to 16 days at 20°C (DeLoach & Cordo 1976). Newly hatched larvae (1 mm long) tunnel downwards to the base of the petiole and into the plant crown where they may damage axillary buds. Damage by larvae destroys tissue causing discoloured streaks along the lower petioles. The third and final instar larvae (up to 4 mm long) exit the crown and move to the roots where they construct a dark coloured, circular (2 mm diameter) cocoon of root hairs attached to a larger rootlet under water (Center 1994). On emergence the new adults move up the plant and commence feeding within 24 hours. The development durations varied in different studies (Julien *et al.* 1999), however, development takes longer for *N. eichhorniae* (96 to 120 days) than for *N. bruchi* (72 to 96 days). The optimal temperature for oviposition, feeding and development in both species is around 30°C. Eggs will not develop below 15°C and 20°C in *N. eichhorniae* and *N. bruchi* respectively (Julien *et al.* 1999).

Niphograpta albiguttalis

This moth, previously referred to as *Sameodes albigutallis* (Warren), is the next most widely used biological control agent after the *Neochetina* weevils. It is native to and widespread in South America on water hyacinth. Its host-specificity testing has involved 136 plant species from 60 plant families and the results are detailed in Julien *et al.* (2001). *Niphograpta* is specific to plants in the family Pontederiaceae and has strong preference for water hyacinth. It is established in six of the 13 countries in which it has been released (Julien 2001; Julien *et al.* 2001).

This is a small moth with wingspan of 17 - 25 mm and body length 6 - 10 mm. Colour is variable; wings being golden-yellow to charcoal grey with brown, black and white markings (Center 1994). The body has similar coloured light and dark stripes. The moths rest on the underside of leaves by day and are active at night. Female moths are darker and larger than males. The posterior of the abdomen is more pointed in males and is usually held upwards more than in females. Most eggs are deposited singly or in small groups in lamina and petiole tissues, often injury sites, during the second and third night after emergence (DeLoach & Cordo 1978). Adults live 4 to 9 days and females lay an average of 370 eggs (DeLoach & Cordo 1978; Center 1994). Eggs are 0.3 mm diameter, creamy white, and hatch in 3 to 5 days (Julien *et al.* 2001). Hatchling larvae, ca 1.5 mm long, feed externally initially and then internally causing characteristic 'windows' in the epidermal tissues of petioles. There are five larval instars and as larvae grow older they tunnel deeper into the tissues and eventually into the plant crown. Final instar larvae are about 2 cm long and larval development requires 16 to 21 days (DeLoach & Cordo, 1978; Center, 1994). Severe damage to internal tissues causes leaves to wilt and die. Feeding in the crown area may destroy the apical buds and the entire ramet, causing the plant to rot and sink. Plants may regenerate through the growth of axillary buds. Pupation occurs in a chamber made in the aerenchyma tissues of a petiole, with a tunnel that leads to the petiole surface where a thin layer of epidermal tissue is left intact for protection. Pupae are encased in a white silken cocoon from which the adults emerge after 5 to 7 days and exit the petiole via the tunnel, breaking through the thin 'window'. One generation takes 27 days at 24°C (DeLoach & Cordo$_2$ 1978).

Populations of *Niphograpta* can increase quickly under favourable conditions and rapid dispersion averaging 1 km/day (up to 4 km per day) has been observed (Center$_2$ 1984). *Niphograpta* prefers young, tender plant material, possibly due to young larvae being unable to enter older, tougher petioles (Wright & Bourne$_2$ 1986). Hence larvae and pupae of this moth tend to be found in the small, bulbous petiole form of the weed, characteristic of uncrowded growth at the edge of water hyacinth infestations (Julien *et al.*$_2$ 2001). However, they are not restricted to this plant form (Center$_2$ 1984). Because moths select oviposition sites in healthy, undamaged plants, the damage they cause to water hyacinth is often severe but patchy (Wright & Bourne$_2$ 1986). Damaged plants that are not killed may re-grow from intact buds. Although it has not been possible to quantify the impact of this moth , the moth is considered a valuable control agent because it selectively attacks new growth and appears to reduce the rate of invasion of the weed (Wright 1984; Center$_2$ 1987).

Xubida infusellus

Xubida infusellus was previously referred to as *Acigona infusella* (Walker). It is also widespread on the plant in South America. This moth has undergone host test studies in six countries and tests included 66 plant species in 30 plant families. It is restricted to feeding and developing on plants in the Pontederiaceae family (Bennett & Zwolfer$_2$ 1968; Silveira-Guido$_2$ 1971; DeLoach 1975; DeLoach *et al.*$_2$ 1980). *Xubida* has been released in three countries, Australia, PNG and Thailand and has become established in the first two. It has not been released in USA because it

attacks *Pontederia cordata* L., a native of southern USA (Julien *et al.*$_2$ 2001).

Xubida is a delta-winged moth 20 to 25 mm long and tan to red-brown in colour. Males are smaller than females. Females live 4 to 8 days. By day the moths rest on petioles and they are active at night. Males emerge from pupae before females and mating occurs on the first night with most oviposition occurring over the next - 2 to 4 nights (Julien & Stanley$_2$ 1999; Julien$_2$ 2001). Clusters of eggs up to several centimetres long and containing 14 (DeLoach *et al.*$_2$ 1980) to 171 eggs (Sands & Kassulke$_2$ 1983) are deposited in white gelatinous masses on leaves and petioles, especially along the grooves where leaves overlap. Individual eggs were 0.8 mm x 0.5 mm and creamy white. Eggs hatch in 6 to 11 days (Sands & Kassulke$_2$ 1983; Silveira-Guido$_2$ 1971). Newly hatched larvae, 1 mm long, disperse by lowering themselves on silken threads or walking to a feeding site. They enter the petiole and sometimes cause characteristic damage by girdling and killing the upper portion of the petiole and the entire lamina. Larvae then tunnel downwards to the lower petiole and into the plant crown and rhizome. Larvae developed through 7 to 10 instars taking on average 48 days (Sands & Kassulke$_2$ 1983). The final instar larva are up to 25 mm long (Julien *et al.*$_2$ 2001) and they cut a pupation chamber with an exit tunnel to the petiole surface, leaving a thin window of epidermal tissue for protection. There is no pupation cocoon and pupation requires eight days at 25°C. The pupal case may be left projecting from the emergence tunnel as the adult exits the plant (Bennett & Zwolfer$_2$ 1968). The life cycle requires about two months at 25 - 30°C (Julien *et al.*$_2$ 2001).

Of all the natural enemies tested for water hyacinth, *X. infusellus* was claimed by DeLoach (1975) to be the most damaging insect. DeLoach *et al.* (1980) observed in Argentina that most *X. infusellus* damaged plants died, reducing the cover from 50% to between 5 and 10% in a lagoon during one year. They prefer the long slender petioles and only occasionally damage the bulbous ones.

METHODS

Surveys for water hyacinth and control strategy decisions

Laup (1987) reported 30 infestations of water hyacinth in 12 provinces in PNG. He included the Sepik River and associated lagoons as one infestation. About half of these required confirmation that they were indeed water hyacinth. Early in the project (early 1993) it was realised that there were many unrecorded infestations in PNG. Information about location of infestations was sought in several ways; through a survey conducted via the agricultural magazine Didimag, displays at agricultural and province shows, radio 'didiman', awareness displays at markets in major centres, and community and individual discussions. Reported infestations were visited to confirm that water hyacinth was present and to decide on and instigate actions to be taken. Follow up visits either implemented actions or assessed their outcomes. To achieve this most infestations were visited a number of times. All water hyacinth infestations were entered into a database that included information on location, date found, the person who confirmed the weed, control action taken, when and which agent(s) were released or if removal had been advised. Follow-up details were also recorded such as dates, confirmation that the agent(s) were established or that removal had been carried out. The very large infestation in the Sepik River catchment was entered into the database as nine locations; lower and middle Sepik, Chambri Lakes, Wom Grasslands and the five main river tributaries; Karawari, Krosmeri, Keram, Pora Pora and Yuat Rivers.

Infestations of water hyacinth that were small and accessible, isolated from other infestations, and threatened catchments that were otherwise free of the weed were considered for eradication. Sites where it was grown as an ornamental or as stock feed were also marked for eradication. At such sites, discussions were held with the landowner, village elders or tenants and advice was given to hand remove, sun-dry and burn the weed. Vigilance and repeated removal of regrowth was also stressed. In the majority of cases this was successful. Where it was not successful, biological control agents were released. The exception was in ornamental situations, such as hotel or household ponds and drains, where reminders of the threat the weed posed to the environment and the illegality of growing the weed always resulted in co-operation.

At all sites where eradication was not feasible biological control was instigated. To do this biological control agents were either reared or collected from the field and released onto the weed at those sites.

Rearing of biological control agents

The *Neochetina* weevils were reared in commercially available above-ground pools. These were constructed on flattened ground and comprised a thin sheet of metal 9.4 m long x 0.6 m wide with ends bolted together to form a circle 3 m diameter x 0.6 m deep and over which was fitted a plastic liner. The pools were filled with water to

20 cm below the top, and Aquasolâ, a soluble complete fertiliser, was mixed into the water at a rate of 200 g per pool. Healthy water hyacinth plants were collected from the field and added to cover the surface of the pools. Two hundred adults of either *N. bruchi* or *N. eichhorniae* were placed on the plants in each pool. Six pools were set up, initially at Saramandi Research Station near Angoram, and later moved to Angoram, on the Sepik River. Similar rearing was conducted at Kila-Kila Agricultural Station, near Port Moresby, using 2.3 m diameter x 1 m deep metal water tanks as well as several of the plastic lined pools.

The fertiliser was added to the pools approximately every month, plants other than water hyacinth, eg. *Salvinia molesta* or *Utricularia*, were removed as required and water levels were maintained. After eight weeks, when the first new generation of *Neochetina* adults began to emerge, adults were harvested. Thereafter, harvesting was carried out approximately every week. To do this, the plants were submerged under steel mesh sheets weighted with stones and adults were collected as they floated to the surface of the water. Harvesting was limited so that sufficient adults remained on the plants to ensure continuation of the population. The collected adults were counted and held in plastic containers on water hyacinth leaves until they were transported and released in the field. Fresh, healthy, water hyacinth plants were added to the pools as required and approximately every 9 - 12 months each pool was emptied, cleaned and set up with new plants and insects to maintain production levels.

Neochetina eichhorniae were reared using insects collected from the field near Angoram in the lower Sepik River in PNG. *N. bruchi* rearing began with insects imported from Australia. In addition, *N. bruchi* adults from Australia were either shipped or hand-carried on direct flights from Brisbane to Port Moresby under PNG import permits. These insects were from healthy colonies maintained in plastic lined pools at CSIRO Long Pocket Laboratories, Brisbane, and none had been field-collected. Adults were transported in plastic food containers 11 cm diameter and 11 cm deep with a piece of damp cloth and up to 250 adult weevils per container. In a laboratory in PNG the weevils were repacked with 100 to 200 adults per container and with water hyacinth leaves collected in PNG. Containers were packed into insulated boxes to protect the insects from heat and direct sunlight during transportation to the field.

Niphograpta albiguttalis was reared in Australia under laboratory conditions using a healthy colony that was regularly checked to ensure that it was free of disease. Attempts to rear in PNG were unsuccessful partly because of poor laboratory facilities. In Australia adult moths were reared in a 3 m diameter x 0.6 m deep plastic lined pool that was surrounded by a 4.5 m square frame covered with shade cloth to prevent the moths escaping. Moths were collected and paired (one or more males to one female) and held in containers on water hyacinth leaves - with grooves made in the upper epidermis. Females laid eggs in the grooves and every 24 hours the moths were provided new grooved leaves. Leaves with eggs were held in a laboratory at 25 to 27°C until they hatched (4 to 5 days) when other leaves were added. Fresh leaves were added and old leaves discarded several times each week until the larvae had developed to about third instar (approximately 1 cm long). At this stage the leaves with larvae were packed into 11 cm diameter x 11 cm deep plastic containers amongst fresh leaves and transported to PNG under appropriate import permits. In PNG the containers were opened in a sealed laboratory and the larvae were transferred to clean containers and fresh water hyacinth leaves. The used containers and plant material from Australia were sealed in plastic bags and immediately burnt.

The larvae were either taken to the field for release or placed on small bulbous water hyacinth plants in rearing pools and some time later the plants with insects were placed in the field. Larvae that were taken directly into the field were either placed on bulbous petioles of field plants or inserted into petioles by cutting a small hole and carefully placing a larva inside the plant and replacing the cut piece of plant. Sometimes the plants with larvae were held in floating screened cages, 0.5 m x 0.5 m 0.5 m high, covered with shade cloth, to prevent emerging moths dispersing before mating. Cages were removed after three weeks on the assumption that larvae would have completed development, and adults would have emerged, mated and laid eggs. At other times, the plants with larvae were held in the same general area by setting up floating logs or bamboo. These techniques held the plants with insects in the same place and permitted post release observations.

Xubida infusellus was reared in Australia and transported to PNG for release and also reared in PNG. In Australia, a population of this moth was maintained in a caged pool from which pupae (which were held in petri dishes until adults emerged) or adults were collected. One female and one or more male adults were placed in an 11 cm diameter x 11 cm deep plastic container with a cover of nylon mesh that was folded to form an overlap groove along which females deposited their eggs masses. New mesh covers

were provided daily. Sections of mesh with egg masses were cut out and placed into small containers until eggs hatched; 6 - 7 days at 25°C. The mesh with hatchling larvae was then placed in a plastic container with about ten 5 - 8 cm lengths of freshly cut, slender water hyacinth petioles. The larvae entered and fed on the petioles. As petioles deteriorated, fresh sections were added to the container allowing larvae to move into better material. To complete larval development, each larva required three or four petiole sections. Pupae were carefully extracted from the petiole sections and held in containers. The resulting adults were added to the caged pool or used to obtain eggs and larvae for PNG.

Eggs on mesh or young larvae in petiole sections were transported to PNG with appropriate import permits. In a sealed laboratory, petioles were split open and the larvae were extracted and placed onto sections of petioles collected from PNG water hyacinth. The used containers and Australian plant material were burnt. Some eggs and larvae were added to rearing pools located at Kila-Kila Agricultural Station in Port Moresby. Pupae were collected from the pools and rearing was carried out to obtain egg masses and larvae for release. Eggs and larvae were placed in containers on cut sections of petioles and taken to the field for release. They were transported in containers in insulated boxes for protection. In the field pieces of mesh with eggs were pinned to laminae and petioles of plants. Sections of petiole containing larvae were pinned onto field plants, either directly onto a petiole or rolled into a lamina.

Male moths emerge earlier than females and so repeated releases were made where possible to improve the chances of female moths encountering males, eg., at Magendo No. 1 Lagoon in the Sepik River, releases were made on 21 June, 26 June, 3 July, 10 July and 17 July in 1997.

Releasing and monitoring

Release sites were accessed by foot, vehicle, boat, and, inaccessible locations such as the Wanggoe River in Western Province, by helicopter. Sites were selected for stability so that where possible the plants and insects would not be removed during normal flooding. Surveys for the weed attempted to locate the uppermost infestations in a catchment and initial releases were made at those locations so that any movement of plants downstream would also help spread the insects. All releases were entered into agent specific databases. Included were; site details, agent and numbers released, date(s) of release(s), the origin of the insects (Australia, PNG rearing pools or field collected). There were many more release sites than water hyacinth locations. For example, the locations database included nine locations of water hyacinth in the Sepik River catchment, however, the release site database for the *Neochetina* weevils listed 298 releases at 76 sites in the Sepik River system.

Post release observations were made at regular intervals at selected sites and whenever possible at all other release sites. The weevil species and presence or absence of characteristic *Neochetina* adult feeding scars on the leaves and petioles was noted. For the moths, the presence of characteristic petiole damage and presence of larvae or pupae in the plants was noted. For *Xubida*, Delta traps baited with an artificial pheromone (Stanley *et. al.*,$_2$ 2000) were also used to detect presence of adult males.

RESULTS

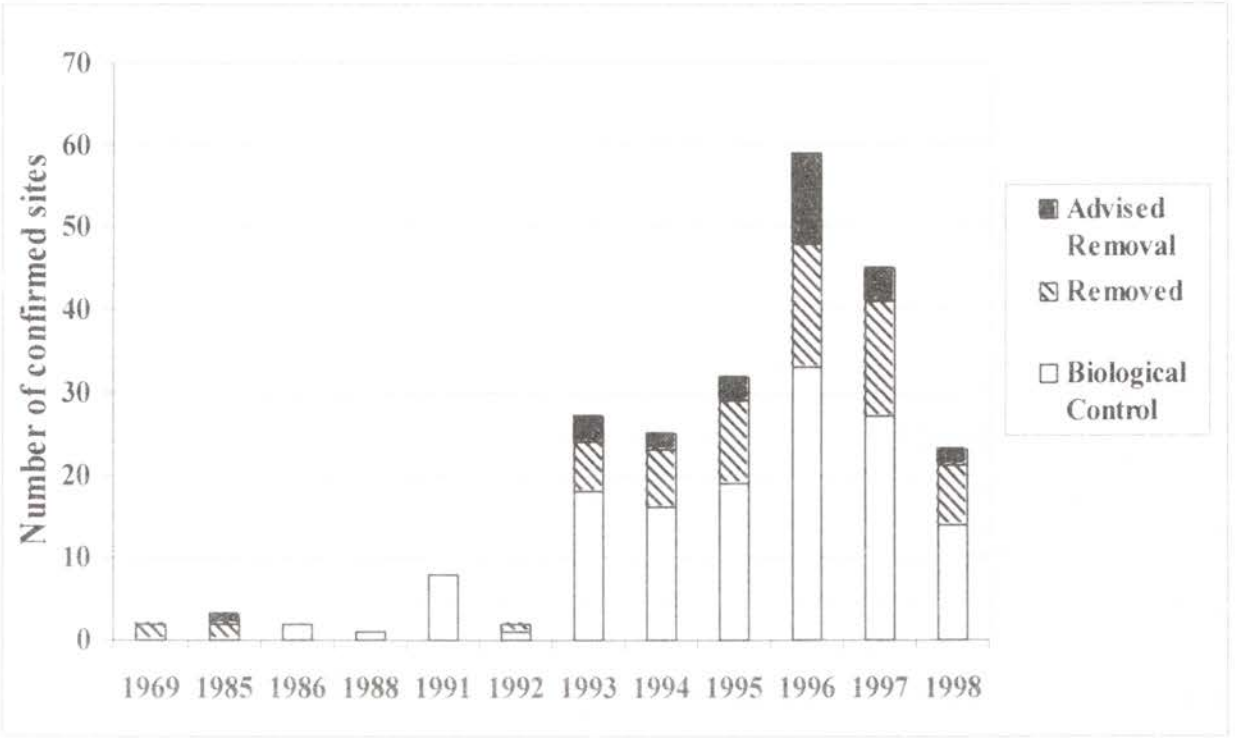
Water hyacinth infestations and their control

Two hundred and twenty nine infestations of water hyacinth were confirmed in PNG with the weed occurring in all provinces. The number of confirmed infestations per year increased dramatically when the project began and again in 1996 when an Information Officer was employed and greater emphasis was placed on public awareness. The data suggests that additional infestations would continue to be identified after 1998 but at a rapidly reducing rate (Figure 1).

Ninety infestations were considered eradicable by removal. At 64 of these the weed had been removed and had not re-grown when checked during follow up visits. The remaining 26 required follow up to determine if removal had been carried out and if it was successful. By the end of December 1998, 139 out of 229 water hyacinth infestations found in PNG had one or all of the biological control agents released on them. There also remained 33 unconfirmed reports of water hyacinth infestations. Some were to be assessed by district officers and others were in restricted locations or those difficult to access, such as parts of Bougainville. An indication of the control actions instigated with respect to the number of reports of water hyacinth in individual provinces in PNG is illustrated in Figure 2. In addition, numerous reported infestations were found to be other plant species, most often *Monochoria hastata* (L.) Solms-Laub., *M. vaginalis* (Burman f.) C. Presl ex Kunth, and *Sagittaria platyphylla* Michaux.

In 1991, 13 lagoons in the Lower Sepik were infested with water hyacinth and the upper most infestation was in a channel leading from the Sepik River into Pesosat Lagoon, west of Timbunke. By 1997, the weed had moved upstream to

Figure 1. **The number of water hyacinth locations identified each year and the control strategy implemented.**



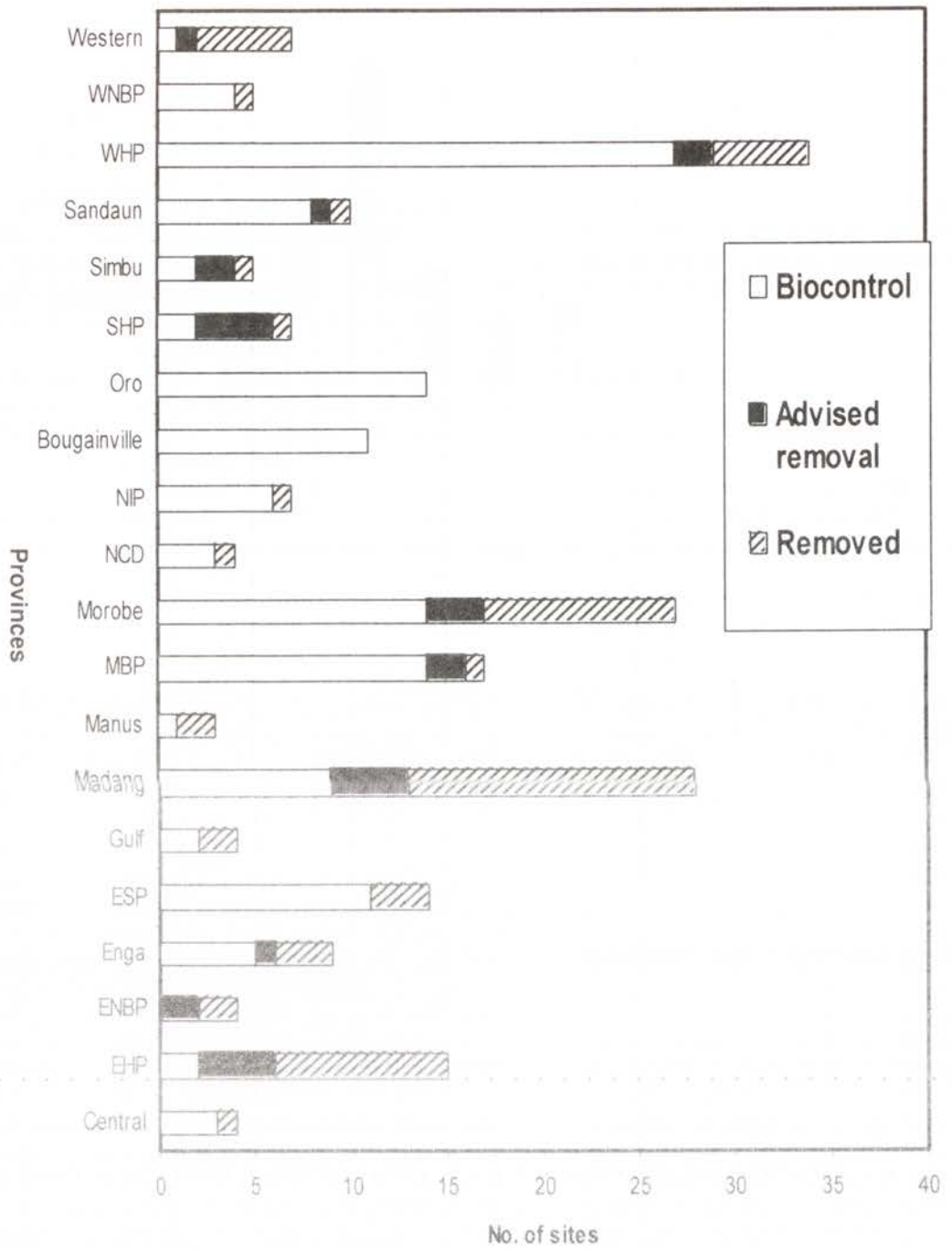
Chambri Lakes and by 1998 it had invaded Kamangawi Lagoon just north of Chambri Lakes. In August 1998, Chambri Lake and 37 other major permanent lagoons, many minor ephemeral water bodies, as well as hundreds of kilometres of the banks on the Sepik River and associated channels and tributaries were invaded by the weed.

Release and establishment of the *Neochetina* weevils

Neochetina eichhorniae was not found on the water hyacinth at the original (June 1985) release sites, an urban drain near Finch Street, Madang, and along the Madang to Bogia Road. This weevil had been established at Finch Street at least temporarily because in July and August 1986 adult *N. eichhorniae* were collected and released at Bulolo and into rearing tanks at Saramandi Research Station near Angoram (P. Pandau, pers. comm.). A further collection was made in September 1988 and these adults were released directly on water hyacinth in the Sepik River near Angoram. This release site was flushed away during the 1988-89 wet season (S. Laup, pers. comm.). The release at Bulolo resulted in control of water hyacinth in several gold mining ponds prior to 1991. In February 1988 weevils collected from Bulolo were released on water hyacinth in Nainkain Creek, Saidor, Madang Province (P. Pandau, pers. comm.), but they failed to establish as no evidence of the weevil was found in 1995. Eight releases at four sites in the Lower Sepik were made between March and August 1989 using adults reared at Saramandi Research Station. These releases averaged 96 (50 to 120) adults. During 1992, adults collected from the field were released at four other locations in the Lower Sepik, and averaged 132 (100 to 230) adults per site (P. Pandau, pers. comm.). In 1993 populations of *N. eichhorniae* were found in lagoons south and west of Angoram town as far as Magendo No.1 Lagoon, Mamu (Karnbaramba) Lagoon and Magendo No. 3 Lagoon. No evidence of establishment was found where releases had been made further west near Tambunum Village (Sept. 1992), south along the Keram River (April 1992) or along channels in the Wom Grasslands (Sept. 1992). Hence, despite *N. eichhorniae* being established in parts of the Lower Sepik since 1989, by 1993 they had not spread throughout the areas infested, and some releases had either not survived or had been flushed away during the wet season.

The renewed rearing of *N. eichhorniae* in PNG, which began in early 1993, produced 234,649 adults. Another 100,754 were collected from the field, mostly from the Lower Sepik. Therefore a total of 335,403 adult *N. eichhorniae*

Figure 2. **The number of water hyacinth locations by province in PNG and the management strategies instigated to December 1998.**



were distributed throughout PNG in 429 separate releases, at 191 sites that included all of the 139 water hyacinth locations that received biological control agents. Beginning in late 1993, 93,694 *N. bruchi* adults were reared in PNG, 86,360 others were reared in Australia and transported to PNG for release. After this insect became well established in PNG, another 24,627 adults were collected from the field in PNG and redistributed. Together 339 separate releases of weevils were made at 150 sites throughout PNG. Most release sites received both weevil species. However 45 sites received only *N. eichhorniae* while 16 sites received only *N. bruchi*. The first releases of *N. bruchi* in PNG were made at Tambali Lagoon, Sepik River, on 24 March 1993, and at a Waigani sewage pond, near Port Moresby on 1 April 1993.

The smallest single release of the *Neochetina* weevils was 12 adults, the largest 6,000 and the average was 778. Many sites received multiple releases, eg. six releases at Chambri Lakes comprised 12,175 *N. eichhorniae* and 9,727 *N. bruchi* between Dec 1996 and Nov 1998. Single releases of large numbers were attempted when revisiting was unlikely because of the high cost of accessing sites. For example, during a helicopter survey for the weed in the Wanggoe River area on the border with Indonesia in Western Province, releases were made of 5,490 *N. eichhorniae* and 1,543 *N. bruchi* adults on water hyacinth in two places. Elsewhere, collaborators (usually DAL or quarantine officers) collected air-freighted insects and released them at predetermined locations. This ensured wide distribution of the insects and greatly improved the potential to control the weed throughout PNG.

Where *Neochetina* weevil populations caused consistent damage to the weed over a number of years, e.g. in the Lower Sepik River lagoons, flowering was reduced to practically zero and the overall foliage colour darkened, sometimes developing a coppery sheen. Plants became stunted as new leaves failed to thrive and older leaves died. Leaf and petiole length declined, lamina area, ramet (daughter plant) size and weight decreased and newly produced offshoot ramets were fewer and smaller (Julien & Orapa, unpublished data). Tunneling by one or several larvae led to water logging, which reduced the plants ability to float, and led to invasions by pathogens that caused secondary infections. A result of the combined damage in the Sepik lagoons and channels was that the large mats of water hyacinth that previously clogged waterways either sank or fragmented into much smaller clumps of plants. These were then much easier to navigate between, had a lower tendency to clog channels and were easily flushed out of lagoons and channels into the main river and hence to sea.

Release and establishment of the moths

The first release of *N. albiguttalis* in PNG was at Magendo No. 1 and Pinang lagoons in the Sepik on 16 August 1994 when 89 larvae were inserted into petioles and the plants were placed inside a small screened cage and another 84 larvae were placed on plants in the open. Up to August 1995, a total of 8,332 larvae were released in PNG at 16 locations in the Western Highlands (WHP), East Sepik (ESP), Western, West New Britain, and Central provinces and the National Capital District (NCD). More than half (57%) of the total number of larvae were released at ten sites in the Lower Sepik where, by boat, it was easy to access the young, rapidly growing plants, normally found on the water margins of water hyacinth mats, that are preferred by the moth. The number of larvae per release averaged 269, and ranged from 50 - 1,200. Four releases were made at the same location on the Maramba to Sangriwa channel in the Lower Sepik area at intervals of three to four weeks in an attempt to establish a field population by repeatedly releasing insects to the same site. Post release monitoring found characteristic plant damage and evidence of pupation at several sites soon after releases in the Sepik. However, no further evidence has since been found and it is concluded that this moth failed to establish in PNG.

The first releases of *X. infusellus* in PNG were made at Waigani Lake on 4 May 1997 and on Magendo No. 1 Lagoon in the Lower Sepik, on 11 March 1997. Releases totalling 59,670 larvae and 54 pupae were made at 12 sites in WHP, ESP, Morobe and Madang provinces until February 1999. Monitoring found plant damage on one occasion in the Lower Sepik but no further evidence of this moth. Male moths were found in Delta traps placed at the Waigani Lake release site six months after release. Considering the life cycle of this insect, the moths caught were at least the third field generation, confirming that breeding had occurred in the field. A year later, in September 1998, moths were again caught, this time between 100 and 200 m from the release site, suggesting that the insect was established at Waigani Lake. A week later a characteristic emergence hole in a petiole with the pupal case protruding was found at Gerehu Lake, a smaller lake adjacent to Waigani Lake.

DISCUSSION

This nation-wide project was particularly successful. Initially, the main targets areas were the large water hyacinth infestations on the Sepik River lagoons and on Waigani and Gerehu Lakes, in

National Capital District. Excellent to good control was achieved at those areas (Julien and Orapa unpublished data). In addition, numerous small infestations were found throughout PNG. The fact that these infestations had not yet spread to their full potential suggested that the project began at a time when the weed was still spreading. Elimination of some of the infestations and the instigation of biological control at others may not prevent the eventual invasion of all catchments by the weed. It will, however, help protect catchments from becoming over-run by the weed. The success of the project is attributed not only to the activities of the *Neochetina* weevils but also to an effective management structure, and an adequate period of time (six years) during which appropriate resources (staff, funds and equipment) were available (Julien & Orapa$_2$ 1999). Inadequacies in design, implementation, time and resources are known to limit the success of biological control projects even when control agents with proven capabilities were used (Waterhouse and Norris$_2$ 1987).

The movement of water hyacinth into and within PNG invariably occurred as a result of activities by people. Most movements were deliberate with people growing the weed as an ornamental or as animal food. Movement within a catchment was sometimes accidental or done in ignorance when the weed was caught on boats, fish nets or used to cover freshly caught fish. The awareness component of this project aimed to significantly alter the general perception of the public that water hyacinth was a desirable plant and thus reduced the rate at which it was being spread. From a general change in the public knowledge about the weed we believe that perceptions were changed. However, it has not been possible to quantify this.

Ideally, now that the *Neochetina* weevils are widely established, any plants that are moved will contain adults or immature stages of the weevils and so the weed's potential for growth, flowering, seed-set and expansion will be limited from the outset as the weed enters its new environment. Realistically, there will be a continuing need for the PNG government to monitor water hyacinth growth in some areas and, if necessary, collect and redistribute weevils. For example, the Fly River catchment is thought to be free of the weed after ornamental plantings in Tabubil and Kiunga were destroyed. When water hyacinth eventually invades that catchment, it will be essential to ensure that the weevils are present early in the invasion so that they can reduce growth and rates of seeding to avoid a repeat of the significant sociological and ecological damage that occurred in the Sepik River system.

The impact of *X. infusellus* may become apparent as populations increase but after its initial establishment in 1998 at Waigani Lake, its population remains small and its impact insignificant. Besides the moth *N. albiguttalis*, which failed to become established in PNG, two other agents, the moth *Bellura densa* Walker and the sucking bug *E. catarinensis*, were given initial consideration for release in PNG during the project, but as more information became available they were rejected. Center and Hill (1999) determined that the moth attacked a number of other plants species in the family Pontederiaceae and also the important crop taro, *Colocasia esculenta* L. (Schott). The sucking bug attacked other plant species in the Pontederiaceae, including *Monochoria* species. Its high mobility and short life cycle put *Monochoria* species that are native to Australia and PNG, at possible risk (Julien & Stanley 1999).

Although control has been achieved in some areas, such as the Sepik River and Waigani Lake (Julien & Orapa, unpublished data), the full impact of biological control by the *Neochetina* weevils on water hyacinth in PNG is not known. Assessment is required at many sites where releases were made three or more years ago (1998 or before). The effectiveness of the *Neochetina* weevils is known to be limited by a range of factors (Julien 2001). Low temperatures may limit insect population growth and therefore control. Floods may remove the weed and insect populations periodically disrupting the insect/plant interaction. Invariably, after the floods the remnant weed grows faster than the insects and may clog the waterway until the next clearing flood. Similarly, drought may destroy water hyacinth biomass and hence the insects but a new infestation, without insects, may develop from seeds once wetting occurs. Shallow water may prevent insect damaged water hyacinth from sinking. Roots of water hyacinth embedded in mud may limit pupation by *Neochetina* weevils and so restrict population development. Consequently, efforts to improve biological control have been carried out. Surveys for new natural enemies in South America and the assessment of organisms continues in the search for new safe biological control agents against water hyacinth (Cordo 1999; Julien & Stanley 1999; Center & Hill 1999; Evans & Reeder 2001; Oberholzer & Hill 2001). When proven useful elsewhere, consideration should be given to releasing them in PNG to help in the ongoing management of water hyacinth.

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