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Managing weeds in tropical wetlands: Wetland risk assessment and *mimosa pigra*

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MANAGING WEEDS IN TROPICAL WETLANDS: WETLAND RISK ASSESSMENT AND *MIMOSA PIGRA*

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Abstract

Weeds are an increasing threat in tropical wetlands. This has been recognised in a number of fora and various recommendations have been passed in an attempt to focus more attention on the problems. The most recent has been the adoption by the Ramsar Wetlands Convention of a resolution on invasive species. This was supported by a report from the Global Biodiversity Forum 13 which also highlighted international efforts to coordinate efforts to combat invasive species in wetlands.

The Ramsar Convention also adopted a further and possibly far more important resolution that encouraged the use of formal wetland risk assessment procedures when addressing threats to wetlands. In assessing the means of managing the troublesome pan-tropical weed *Mimosa pigra* we have used such a procedure. In this paper we report on our efforts to collate the information necessary to make such a formalised assessment. In doing this we describe the nature of the plant and the problems it causes, along with a description of control methods. This information is presented for discussion and further assessment.

1.0 Introduction

Tropical wetlands are renowned for providing many values and benefits for people and for supporting a diverse and plentiful biota (Finlayson & Moser 1991, Dugan 1993). There is also increasing pressure on such wetlands as the pressure of human populations increase and development impacts both the wetlands themselves and their catchments. Responses to such pressures have varied and as a consequence many wetlands have been lost and degraded. Coupled with this loss we have become increasingly aware that we know very little about the extent and worth of many tropical wetland habitats (see papers in Finlayson & Spiers 1999).

Amongst the many threats facing tropical wetlands we have become more aware of the menace posed by invasive weeds. Across the tropics there are many wetland weed species with some of them being widely distributed, if not pan-tropical. These include *Salvinia molesta*, *Eichhornia crassipes* and *Mimosa pigra*. These species have attracted a great deal of attention with the expenditure of large sums of money and effort on control techniques (Finlayson & Mitchell 1981; Storrs & Finlayson 1998, Douglas et al 1998). In instances there have been spectacular success and these have been well documented, such as that for *S. molesta* in northern Australia (Room et al 1981; Finlayson & Mitchell 1981, Storrs & Julien 1996). In other instances there have been spectacular failures and less publicly available documentation (Rea & Storrs 1999). In many instances there seems to have been little attention given to relevant experience gained elsewhere, resulting in the application of ineffective and even inappropriate management schemes.

Within this context we have collated an information base on the biology and management of *M. pigra* as a case study of the application of a formal risk assessment procedure designed to assist weed managers. Much of the information for this assessment has come from northern Australia where *M. pigra* has been seen as a major weed for more than two decades (Cook et al 1996, Finlayson et al 1998, Douglas et al 1998). The assessment, however, is equally as relevant for wetland managers elsewhere who need to tackle this menace to the productive management and conservation of tropical wetlands.

2.0 Background

Given that weeds are an increasingly serious problem in tropical wetlands we are proposing that management prescriptions are developed at several levels. Critically, for managers and users of wetlands, we require practical techniques and options that take into account local differences, priorities and resource levels. However, for localised effort to be effective we also require a strategic framework that provides the required options and places particular weed infestations and their control into a regional perspective. In effect, we are promoting the adoption of ecological or wetland risk assessment procedures as the basis for effective weed management. The basis for these procedures are those prepared in part for the Ramsar Wetland Conference and presented at the 1999 Conference of the Parties as a resolution entitled “Wetland Risk Assessment”. The need to combat weeds was also expressed during the development of a further resolution presented at the Conference on “Invasive Species and Wetlands”.

A Global Biodiversity Forum held prior to the Ramsar Conference also addressed invasive species and came up with the following definition “An invasive species is a species, often alien, which colonises natural or semi-natural ecosystems, is an agent of change, and threatens native biological diversity.” (Pittock et al 1999). This concept is adhered to in this assessment with the additional recognition that the agricultural diversity and production can also be threaten by invasive species.

3.0 Wetland risk assessment

Over the last decade the concept of environmental risk assessment has developed and expanded from a narrow and precise analysis of quantitative ecotoxicological data to more general and qualitative analyses of environmental problems (Finlayson et al 1999). This has led to the Ramsar Convention on Wetlands recommending a model for wetland risk assessment (Figure 1) coupled with advice on the deployment of early warning systems for detecting adverse ecological change in wetlands. The Ramsar procedures are linked with a concurrent effort to espouse the values of wetlands and the maintenance of their ecological character. The former have been summarised by Finlayson (1996a), as shown below.

- *Functions* performed by wetlands are the result of the interactions between the biological, chemical and physical components of a wetland, such as soils, water, plants and animals, and include: water storage; storm protection and flood mitigation; shoreline stabilisation and erosion control; groundwater recharge; groundwater discharge; retention of nutrients, sediments and pollutants; and stabilisation of local climatic conditions, particularly rainfall and temperature.
- *Products* are generated by the interactions between the biological, chemical and physical components of a wetland, and include: wildlife resources; fisheries; forest resources; forage resources; agricultural resources; and water supply.
- *Attributes* of a wetland have value either because they induce certain uses or because they are valued themselves, and include the following: biological diversity; geomorphic features; and unique cultural and heritage features.

The combination of wetland *functions, products* and *attributes* give the wetland *benefits and values* that make it important to society.

In the context of the Ramsar Wetlands Convention and the wise use of wetlands it is stressed that the use and management of a wetland and its resources should be done in a manner that is consistent with the maintenance of the ecological character of the wetland. Ecological character is now defined as

"the sum of the biological, physical, and chemical components of the wetland ecosystem, and their interactions which maintain the wetlands and its products, functions and attributes."

The qualitative wetland risk assessment model recommended for the Ramsar Convention has been derived from those used for water pollution and ecotoxicological assessments and the more general methods developed for assessing the vulnerability of wetlands to climate change and sea level rise. The model provides guidance for environmental managers and researchers to collate and assess relevant information and to use this as a basis for management decisions that will not result in adverse change to the ecological character of the wetland. Our objective has been to provide a framework for informed decision making. Thus, it is not prescriptive.

The steps in this model are given in figure 1 and listed below:

- Identification of the problem (eg site assessment; site-specific information)
- Identification of the effects (eg field assessment by surveys or surveillance)
- Identification of the extent of exposure (eg level of infestation or concentration)
- Identification of the risk (comparison of the field surveys with extent of infestations)
- Risk management/risk reduction (implementation or alteration of management practices)
- Monitoring (early warning and rapid assessment techniques)

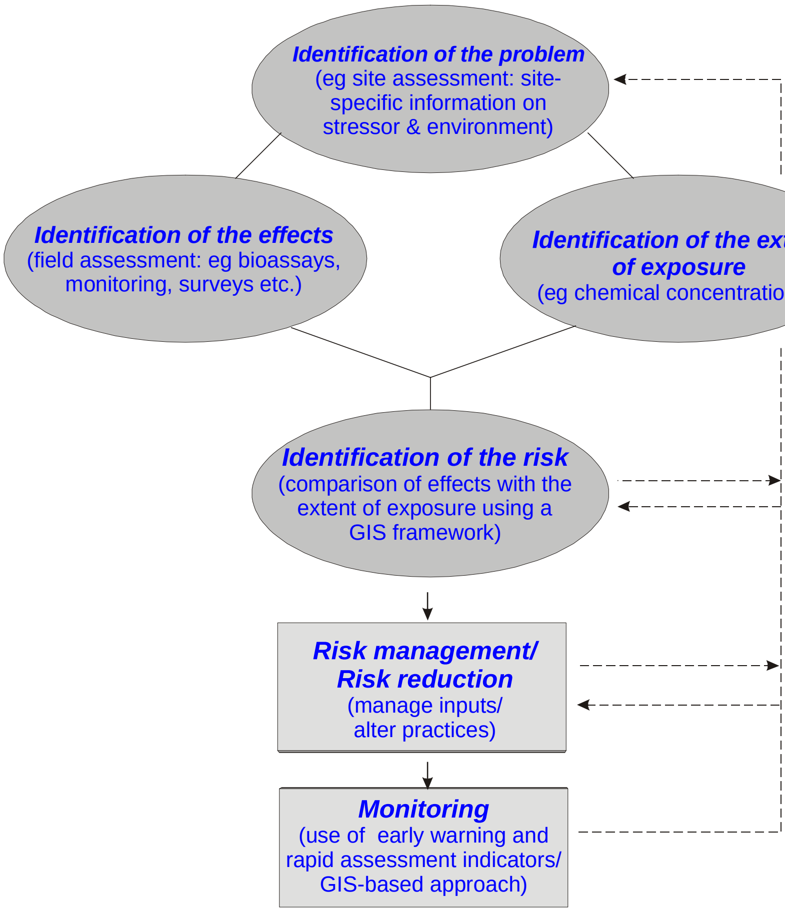

Figure 1 Suggested model of wetland risk assessment

Each of these is described in detail by Finlayson et al (1999) along with an outline of the concept of early warning indicators. Early warning indicators were defined as:

> *measurable biological, physical or chemical responses to a particular stress, preceding the occurrence of potentially significant adverse effects on the system of interest.*

Such indicators generally have some of the following attributes.

i. *anticipatory*: should occur at levels of organisation, either biological or physical, that provide an indication of degradation, or some form of adverse effect, before serious environmental harm has occurred,

ii. *sensitive*: in detecting potential significant impacts prior to them occurring, an early warning indicator should be sensitive to low levels, or early stages of the stressor,

iii. *diagnostic*: should be sufficiently specific to a stressor, or group of stressors, to increase confidence in identifying the cause of an effect,

iv. *broadly applicable*: should predict potential impacts from a broad range of stressors,

v. *correlated to actual environmental effects/ecological relevance*: knowledge that continued exposure to the stressor, and hence continued manifestation of the response, would usually or often lead to significant environmental (ecosystem-level) effects,

vi. *timely and cost-effective*: should provide information quickly enough to initiate effective management action prior to significant environmental impacts occurring, and be inexpensive to measure while providing the maximum amount of information per unit effort,

vii. *regionally relevant*: should be relevant to the ecosystem being assessed,

viii. *socially relevant*: should be of obvious value to, and observable by stakeholders, or predictive of a measure that is,

ix. *easy to measure*: should be able to be measured using a standard procedure with known reliability and low measurement error,

x. *constant in space and time*: should be capable of detecting small changes, and clearly distinguishing that a response is caused by some anthropogenic source, not by natural factors as part of the natural background (ie high signal to noise ratio),

xi. *nondestructive*: measurement of the indicator should be nondestructive to the ecosystem being assessed.

The importance of the above attributes cannot be over-emphasised, since any assessment of actual or potential change in ecological character will only be as effective as the indicators chosen to assess it. However, an early warning indicator possessing all the ideal attributes cannot exist, as in many cases some of them will conflict, or will simply not be achievable.

In the context of risk assessment we emphasise that an early warning indicator is one component of the management regime that is supported by the information contained with the formal wetland risk assessment.

4.0 Case study – *Mimosa pigra*

Based on the theoretical background provided by the wetland risk assessment model we have commenced a case study with the shrub *Mimosa pigra* which is rampant in the floodplain wetlands of the Northern Territory, Australia. This has involved an initial step of reviewing the literature and talking with field operators and wetland managers to identify the following:

- Life cycle features of *Mimosa* and its invasive potential
- Habitat range of *Mimosa* and its likely distribution
- Ecological effects of *Mimosa* and its likely impact
- Economic effects of *Mimosa* and its likely impact
- Control measures used against *Mimosa* and their likely success

In undertaking this assessment we have recognised that *Mimosa* is an acknowledged major weed and that control measures are urgently needed. As such we have focussed much of our initial attention on control measures and their successful utilisation in terms of costs and ease of operation.

As an initial example we report that in one instance 4-6 people have successfully kept *Mimosa* under control across floodplain wetlands covering approximately 230 000 ha through early detection, immediate hand removal and/or spraying with chemicals. However, in adjacent areas highly expensive chemical control programs have been necessary to contain, let alone control large well-establishment stands of *Mimosa*. In addition, biological control agents have been released, but after more than a decade of effort this has yet to prove effective.

Several lessons from the experiences of 1-2 decades of effort in the northern Australian floodplains can be applied to the situation in the Mekong delta and elsewhere in south-eastern Asia. These will be developed with local wetland managers and users as they describe their needs and assess their resources and priorities for weed control. The information collated in this exercise will be used to complete the formal risk assessment, as per the framework outlined in Figure 1, and provide further guidance for managers and researchers on the nature of the weed, its environmental effect and potential for control. The assessment will also identify priority areas for further investigation by field managers and researchers alike.

Thus, the risk assessment for *Mimosa* will likely adopt the following approach: In order to fully understand the problem of *Mimosa*, and hence design an appropriate assessment of risks, information regarding the introduction, biology, spread, extent and effects of *Mimosa*, and the history of control efforts in northern Australia, including their impacts, will be collated. The risks of *Mimosa* to the ecological, cultural and economic values of northern Australian wetlands will be assessed by comparing the documented impacts of the weed to its current and projected distribution. Importantly, any beneficial effects of *Mimosa* (eg potential commercial use; habitat for some native species) will also be considered. In addition, the risks associated with individual and integrated *Mimosa* control methods will also be assessed, by a comparison of their effectiveness in controlling *Mimosa*, adverse ecological impacts, and extent of use. In this way, the relative risks of *Mimosa* and its associated control methods can be evaluated in order to assist in the development of appropriate risk reduction and management decisions.

5.0 Life cycle of *Mimosa pigra* and its invasive potential

The life cycle and general biology of mimosa have been described in recent years (Lonsdale 1992; Lonsdale et al. 1995; Miller 1988; Rea 1998).

Mimosa pigra is a native of Tropical America where it occurs in a wide belt extending from Mexico through Central America, the Antilles, Colombia, Peru, and Brazil to northern Argentina.

Introduced into other areas as an ornamental, a cover crop, or for erosion control, it is now widespread as a serious weed in Africa, India, Thailand, Indonesia, the Philippines, Malaysia, Vietnam and some Pacific islands. In Australia, *Mimosa* is confined to the Top End of the Northern Territory where it has been present for many years.

5.1 Physical description

When mature, *Mimosa* is an erect much branched prickly shrub reaching a height of 3 to 6 m, reproducing by seed and suckers. Stems are greenish at first but become woody, and are up to 3m long. Initially, they are covered with short stiffened hairs, which give it a rough texture. The stems also have randomly scattered slightly recurved prickles 5 to 10 mm long. Leaves are bright green, 20 to 25 cm long and bipinnate, consisting of about fifteen pairs of opposite primary segments 5cm long. Each segment has numerous pairs of sessile, narrowly lanceolate leaflets that fold together when touched or injured and at night. Pairs of prickles sometimes occur between the branchlets on the main leaf stalk.

The flowers are pink or mauve, small, regular and grouped into globular heads 1 to 2 cm in diameter. The heads are borne on stalks 2 to 3 cm long, with 2 two in each leaf axil, while the corolla has four lobes with eight pink stamens. The fruit is a thick hairy, 20-25 seeded, flattened pod borne in groups in the leaf axils, each 6.5 to 7.5 cm long and 7 to 10 mm wide. The fruit turns brown when mature, breaking into one-seeded segments. The seeds are brown or olive green, oblong, flattened, 4 to 6 mm long, and 2 mm wide.

5.2 Advantageous features

Mimosa has many features that are generally considered 'advantageous' to a weed. The greatest problem for plants growing in flooded soils is that their roots drown in the anaerobic conditions. *Mimosa* withstands such conditions by sprouting adventitious roots near the surface, where they can take up oxygenated water. Thus, the thickets can continue their advance until only a tiny remnant of open water remains in the deepest parts of the billabongs (Miller et al 1981, Braithwaite *et al* 1989).

If chopped down *Mimosa* will easily resprout from the stump (Wanichanantakul & Chinawong 1979). If *Mimosa* is burnt, the foliage may become desiccated and fall, but up to 90% of mature plants and up to 50% of seedlings may regrow, probably from dormant buds, which stimulate regrowth from the base and stems after fire (Miller & Lonsdale 1992).

The plants mature quickly and can set seed in their first year of growth. The seeds of *Mimosa* are well designed for easy and rapid dispersal. The seedpods break into segments when mature, with each segment containing a single seed. These segments are covered with bristles that enable them to adhere to animals and clothing, and to float on water for extended periods. The seeds are also dispersed in soil and mud, adhering to vehicles and other machinery (Lonsdale et al 1985). Livestock and native animals sometimes graze *Mimosa* plants and pass the seeds in their dung. Although spending many hours in the gut of an animal, *Mimosa* seeds may still be 70-90% viable.

The lifespan of the seeds in the ground depends greatly on their depth in the soil and the soil type. For example, half of a seed population was no longer viable after 99 weeks at a depth of 10 cm in a light clay soil, while a similar loss in viability was observed after only 9 weeks in a heavier cracking clay (Lonsdale *et al* 1988). In sandy soils, observations suggest that seed lifespan may be as high as 23 years (SE Pickering pers. comm.).

Regular heating and cooling of the soil surface results in a soil temperature range from about 25 to 70°C, causing expansion and contraction of the hard seed-coats of *Mimosa* species, eventually making them crack, breaking their dormancy. The deeper in the soil a seed lies, the less extreme is the temperature range. Thus, seeds buried deeper than 10 cm cannot successfully germinate. However, as they can remain viable for long periods, such seeds could eventually germinate if brought to the surface by cultivation or the actions of animals, even if all the adult plants had been removed.

Seed rate production has been measured between 9000 and 12000 m^{-2} per year depending on the conditions (Lonsdale et al 1988). The most productive plant observed in the field in Australia had a crown of about 8 m^2 and produced about 11000 pods per year, equivalent to about 220000 seeds (Lonsdale 1992a).

If a mere handful of seeds per square metre were to germinate, the resulting plants - with their rapid growth rates and early maturation (it takes as little as six months from germination to flowering) - would form dense stands and start copious seed production all over again. This means that total eradication of *Mimosa* will be very hard to achieve.

The compound leaves of *Mimosa*, like those of several other species in the genus, close in response to electrical, mechanical, thermal, wounding and light stimuli (Simons 1981). It has been claimed that such movements will scare or shake off insect herbivores (Pickard 1973), however, to date, there is no evidence to support this hypothesis.

Under the right conditions *Mimosa* grows quickly, at a rate of about 1 cm per day, and infestations can double in area in one year. It can also withstand droughts, so the six month dry season, although slowing its growth rate and thinning its canopy, does not kill *Mimosa* (Beckmann 1990, Lonsdale 1993a).

5.3 Spread of mimosa in the Northern Territory

Mimosa was probably introduced to Australia at the Darwin Botanic Gardens in the 20 years prior to 1891, either accidentally in seed samples, or intentionally, as a curiosity, because of its sensitive leaves (Miller and Lonsdale 1987). It lingered in the Darwin region causing an occasional nuisance (Swarbrick 1983, Miller and Lonsdale 1987) and was noticed upstream from Adelaide River Township in 1952. It might have remained an occasionally troublesome, but essentially minor weed, had it not been for two other factors: water buffalo and heavy flooding.

By the late 1970s, huge herds of feral Asiatic water buffalo were causing massive damage by overgrazing the native sedgelands, particularly on the flood plains of the Adelaide River. the major problem of over grazing was that the animals removed almost everything, leaving no competition for unpalatable species such as thorny or prickly shrubs, which then take over. This phenomenon has been observed all over the tropics, from Mali to Mexico.

During the wet seasons of the mid-1970's there was particularly heavy flooding. As a result, *Mimosa* seeds were rapidly spread to the bare and highly disturbed soils of the flood plains, which by then had become ideal seedbeds for the weed (Lonsdale and Braithwaite 1988).

In 1975 there were only a few *Mimosa* plants on the Adelaide River floodplain. By 1978 the infestation had exploded to an estimated 200-300 ha of impenetrable *Mimosa*. By 1980 there were plants scattered over an estimated 4000 ha (Miller *et al* 1981), and in 1984 the population was estimated to cover about 30000 ha in dense and scattered stands (Lonsdale 1993a). This rate of infestation demonstrates the high invasive potential of *Mimosa*, given the right habitat and environmental conditions.

At some point the plant escaped from the Adelaide River system and appeared in other areas such as the Daly, Finniss, Mary and East Alligator systems. The documented locations of *Mimosa* in the Northern Territory as of February 1998 are shown in figure 2. Physical removal of seeds by man has been a major factor in spreading *Mimosa* away from the Adelaide River area. Sand removed from the river for use in concrete for railway and bridge culverts has carried the weed to the Batchelor-Run Jungle area (Miller *et al* 1981).

Between 1980 and 1989 *Mimosa* spread from 4000 to 80000 ha (NT Government 1997), a figure which is still quoted in much of the literature produced throughout the decade of the 1990s. This could mean several things:

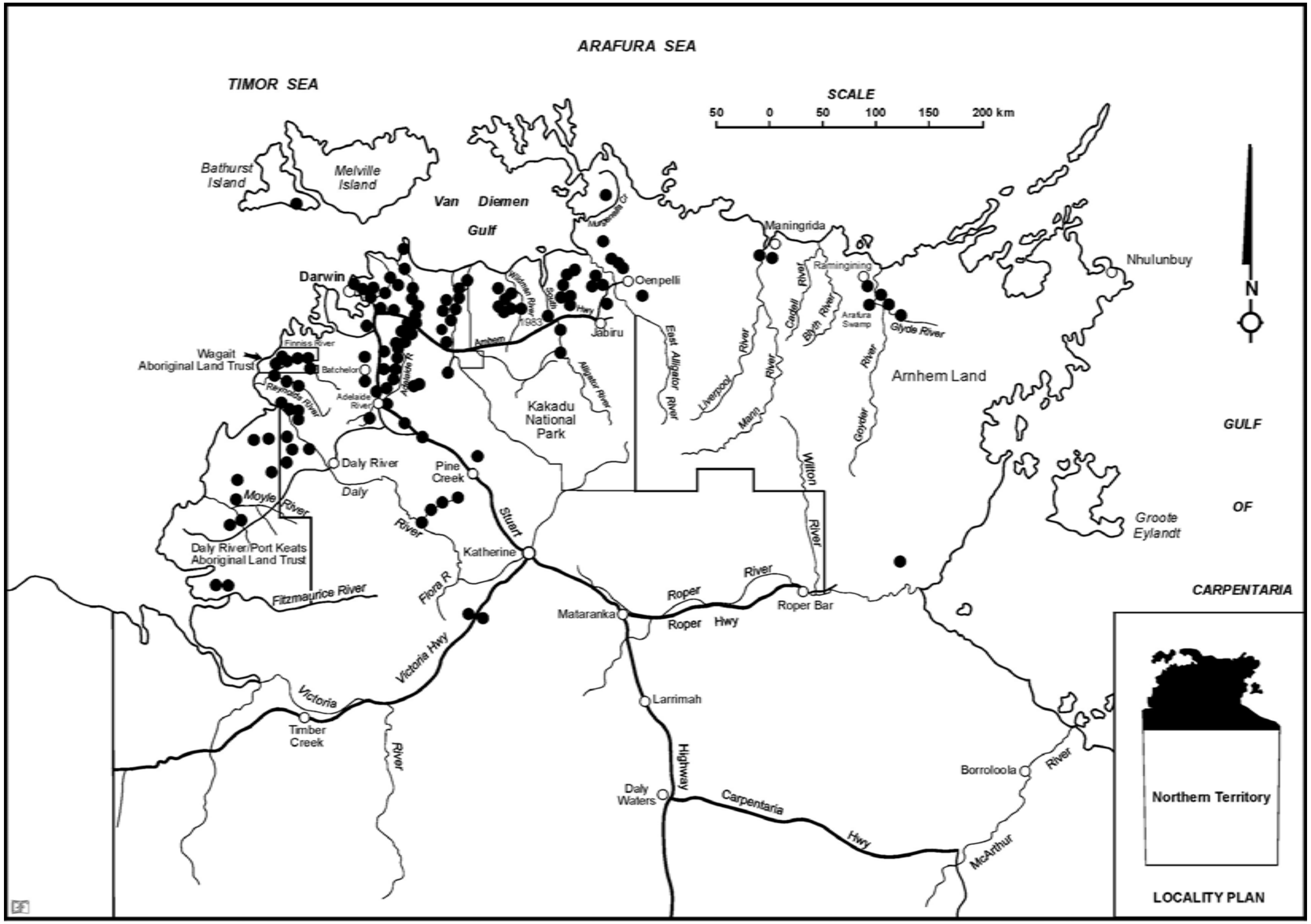

Figure 2 Documented locations of *Mimosa pigra* infestations in the Northern Territory as of February 1998 (from Camilleri et al 1998)

1. That either the control and/or eradication measures in some areas are keeping pace with new areas of spread.
2. The area of all infestations is remaining stable due to control measures.
3. There has been insufficient survey work to update the figure quoted for the area of infestation.

It is likely that the latter explanation is correct, and therefore, it is essential that the accuracy or otherwise of the figure of 80000 ha is verified. Given recent research in the further development of remote sensing techniques for determining *Mimosa* coverage (Lyon et al 1999), such a task should be seen as a priority for future *Mimosa* management in northern Australia.

5.4 Habitat range and likely distribution

Mimosa favours a wet-dry tropical climate and has been introduced into most tropical regions of the world where it grows in comparatively open, moist sites such as floodplains, coastal plains and river banks. In the introduced range *Mimosa* infests disturbed places such as reservoirs, canal and river banks, roadside ditches, agricultural land and floodplains. In Australia and Thailand it forms dense thickets covering thousands of hectares (Lonsdale *et al* 1985, Napometh 1983). In its native range *Mimosa* occupies similar habitats, especially in areas which have been disturbed, but usually occurs as small thickets or as individual plants (Harley 1985). *Mimosa pigra* becomes common in overgrazed areas in Costa Rica (Boucher et al 1983), part of its native range. In some other areas of its native range, *Mimosa* is taking on the status of a weed because of changes in land use practices and the increase of suitably disturbed wetland areas (CM Finlayson pers comm).

The rapid colonisation of *Mimosa* in the Northern Territory has largely been attributed to the availability of disturbed habitat as a result of overgrazing and soil disturbance by feral buffalo, and a subsequent lack of competition from native flora (Lonsdale et al 1988, Lonsdale and Braithwaite 1988).

Except around dams and watercourses *Mimosa* would probably not be a major problem in regions with less than 750 mm annual rainfall (Miller 1983). Because of plant competition, *Mimosa* is also unlikely to succeed in tropical rainforest areas where rainfall exceeds 2250 mm. However, clear-felling in this climate would probably allow the plant to flourish (Lonsdale *et al* 1995). The best indication of the potential spread of *Mimosa* into the subtropics comes from its north American range. The plant occurs in Florida as far north as Gainesville (latitude 29°, W.T. Haller personal communication to K.L.S. Harley), but is not as tall or aggressive as it is elsewhere in its introduced range. This is perhaps because the climate in the region, though warm enough to allow it to persist, has cool winters, with freezing temperatures on average once in every four years (W.T. Haller personal communication to K.L.S. Harley).

In Australia *Mimosa* is not restricted to any one soil type, and Miller (1983) has reported the plant growing on alluvial red and yellow earths, silty loams and black cracking clays. It is very tolerant of seasonal inundation, although glasshouse experiments suggest that permanent inundation would prevent seedling recruitment (Shibayama *et* al 1983).

The precise relationship between the plant's distribution and salinity levels remains to be determined, but water salinity nearby infestations on the lower Adelaide River can reach

18000 ppm late in the dry season (Miller 1983). In 1968 it was thought that the Marrakai crossing would mark the lower limit of the spread of *Mimosa* on the Adelaide River system, as the crossing represents the limit of tidal influences on the river. Its subsequent invasion down to the flood plains has proved this theory to be erroneous (Miller *et al* 1981).

Mimosa has the potential to expand its area considerably in both Australia and Asia. If not controlled it may spread south-west into the northern regions of Western Australia, south-east into Queensland, to Cape York and southwards down the east coast to the Tropic of Capricorn (Miller 1983). This range of expansion would assume that the plant or its seeds will be moved to new suitable habitat either by man or animals, as there is not a continuity of suitable habitat within this range. Lonsdale (1993) stated that the various flood plains that are the main habitat of *Mimosa* in northern Australia are separated by eucalypt savannas, which are not readily colonised by the weed. The plant therefore must move between river systems in quantum leaps, perhaps on vehicles, or carried in mud on animals. It should be noted, however that in a survey of more than 300 tourist vehicles entering Kakadu National Park, no seeds of this plant were found, although other weed species were (Lonsdale and Lane 1994). Irrespective of how the plant was moved from catchment to catchment, it nonetheless has happened in a relatively short space of time.

From an examination of the vegetation types in Kakadu National Park (an area of great biological significance and importance to the tourism industry), and with knowledge of the biology of *Mimosa*, it is estimated that a major infestation could leave 29% of the park covered with the weed. This area at risk includes sedgelands, paperbark forest, monsoon forest and the woodland around rivers, streams and billabongs. In a further 54%, comprising open forest, woodland and shrubland, the weed would become common although not the dominant feature. In only 17%, essentially sandstone woodland, spinifex and mangroves, would *Mimosa* fail to take hold (Braithwaite *et al* 1989). (check ref)

5.5 Ecological effects

Mimosa poses an enormous problem for conservation. In Australia, a largely intact natural landscape is being completely altered, with flood plains and swamp forest being covered by dense monospecific stands of *Mimosa*, which have little understory except for *Mimosa* seedlings and suckers. For native species, the impact of such a change in the habitat is severe. Many animals have become scarce or have disappeared altogether from the Adelaide River region in particular. This is particularly true of ducks, egrets, jabiru storks, magpie geese, and other water birds. In general, *Mimosa* thickets have fewer birds and lizards, less herbaceous vegetation, and fewer tree seedlings than the native vegetation (Braithwaite *et al* 1989).

The loss of wetlands would decimate the waterbird populations, which rely on sedgeland for breeding and feeding. Many wetland areas of the Top End, in particular the Alligator Rivers Region, are already a refuge for species which have disappeared from southern Australia (eg Magpie Goose, *Anseranas semiplamata*) (Frith & Davies 1961). Other common species, such as the Brolga (*Grus rubicundus*), are now much less common in eastern Australia and the region increasingly serves as a refuge (Blakers *et al* 1984). Populations of waterbirds within the region move from one river system to another seeking their preferred environmental condition throughout the year (Morton & Brennan 1990). Their wide-ranging strategy copes with the unpredictably distributed rainfall at each end of the annual wet season, and extraordinarily localised aggregations of waterbirds occur in the dry season. For example, 60-70% of the total population of *A.semipalmata* in northern Australia is concentrated in two or three areas in Kakadu National Park during the late dry season (Bayliss 1990).

The swamp forests fringing the flood plains are dominated by paperbark trees (species of *Melaleuca*). Because these forests have a rather open canopy, *Mimosa* has been able to invade these areas also, forming a dense understory that prevents seedlings of the forest trees from establishing themselves. Once the mature canopy dies out, these swamp forests, like the flood plains and billabongs, will become barren shrubland. The dominance of *Mimosa* in such a range of habitats – (ie open flood plains, billabongs and swamp forests) is without parallel except, ironically, for the invasion of the wetlands of South Florida by a paperbark, *Melaleuca quinquenervia*, from Australia (Lonsdale & Braithwaite 1988).

Studies have been conducted to measure the incident light that is able to penetrate through the weed thickets. It was found that whereas 75% of incident light passed through the canopy of a stand of paperbarks (*Melaleuca* spp.), only 26% made it through to illuminate the ground flora if *Mimosa* also spread its canopy beneath the trees. Sedge-land sites, which carry no trees, received 100% of the sunlight in the absence of the weed, but only between about 60 and 80% if *Mimosa* was present. These measurements represent the situation during the dry season when the weed has a relatively sparse canopy. During the wet, a lush thicket may prevent 90% of the incident light from reaching the ground (Braithwaite et al 1989).

Surveys have revealed that the presence of *Mimosa* does not affect the densities of water buffalo and amphibians. However, it is believed that the numbers of these animals would probably decline in the future, because increases in the area of wetland choked by the weed will make it harder for them, too, to find suitable food (Braithwaite et al 1989).

Some species have increased in numbers as a result of the presence of *Mimosa*. The most notable of these is a rare marsupial mouse called the red-cheeked dunnart (*Sminthopsis virginiae*). In 1986 in the Finniss River area, just three nights of trapping increased the known records for the species by 56%. Nearly all the individuals caught were found just inside the newly weed-dominated former sedgeland. They benefit because predatory birds flying overhead cannot see them, and the clump of above-ground roots at the base of the stems provides an ideal home in which to shelter. However, small mammals will only benefit where the weed occurs in patches from which they can make forays into the surrounding vegetation for food. Once it establishes as a large blanket then these mammals will also find it impossible to live there.

A potential environmental impact that may arise from the presence of *Mimosa* and its subsequent removal is soil erosion. The sudden death of *Mimosa* infestations coupled with the low rates of recolonisation by native species (Parry & Duff 1990) may leave substantial areas of soil unprotected for several years. This is not so much a concern on the floodplains which have negligible slope, but could be a problem on river banks and levees, resulting in increased turbidity in water bodies (NLC Public Environment Report 1991).

5.6 Economic effects

In addition to adversely affecting the natural flora and fauna, *Mimosa* can also affect the activities of man. It interferes with stock watering, irrigation projects, tourism, recreational use of waterways and the traditional lifestyles of indigenous peoples. It can also smother pastures, reduce the available grazing areas and make mustering difficult (Miller et al 1981). In Thailand it is causing sediment accumulation in irrigation systems and reservoirs (Robert 1982), is a safety hazard along roads and interferes with access to electric power lines (Robert 1982, Napometh 1983, and Thamasara 1985).

In many cases the economic impacts of *Mimosa* are contingent with the ecological impacts. The accommodation, recreational, personal and other services sector, of which tourism is the largest component, accounted for 8.5% of Gross State Product in 1994/95. This measure does not take account of Australian produced goods and services purchased by tourists. This sector also employed 20.3% of total employed persons in the NT. In 1995/96 there were 1.3 million visitors to the NT generating expenditure of $718 million. The Territory is an attractive tourist destination because of its natural beauty, wildlife, and frontier image. The quality of the recreational fishing available is a contributing factor to this attractiveness. Tourism and recreation are increasingly important land uses based on natural and cultural values (NT Gov. DPI&F 1999).

A diminishing of the aesthetic beauty of the NT wetlands and a decrease in wildlife numbers due to loss of habitat to *Mimosa* infestations would most likely see a reduction in visitor numbers. This would not only affect tour operators but would flow on to all associated industries such as transport, retail, accommodation, catering and other service industries to name a few, all of whom reap their share of the $718 million.

As early as 1981, the operations of a tourist river safari on the Adelaide River and its tributaries were already affected by *Mimosa*. The Beatrice Creek area abounds with wildlife and was a highlight of the safari, but now part of this area has been removed from the program for the sole reason that *Mimosa* is so thick that access and visibility are affected (Miller et al 1981).

The recreational fishing industry is well established, especially in the Top End with barramundi (*Lates calcarifer*) being a favoured species, and the Mary and Alligator Rivers being very popular destinations (Julius 1996, Griffin 1996). Recreational fishing is also an important part of the Territory economy through expenditure by fishers on their recreational pursuits. Although there are limited data on this sector, surveys conducted during the 1980s document its importance and estimate the recreational sector to be as valuable to the NT economy as the commercial sector. The Cam Rungie/Touche Ross study estimated that over 50 000 anglers fish in NT waters annually, creating expenditure of $60 million per year (NT Gov. DPI&F 1999).

Commercial fishing also occurs, with barramundi and mud crabs (*Scylla serrata*) being targeted (Storrs & Finlayson 1997). The mud crab industry is the most valuable NT wildstock harvest, with an estimated value of in excess of $7.0 million in 1996/97, while the barramundi fishery currently has 26 commercial licenses in operation (NT Gov. DPI&F 1999).

These species targeted for commercial fisheries are intimately dependent on coastal wetlands throughout their life cycles (Storrs & Finlayson 1997), and would no doubt be threatened by the degradation of wetlands under the threat of *Mimosa*. *Mimosa* also impacts on the recreational fishing industry by preventing access to rivers and billabongs (Miller *et al* 1981, Lonsdale *et al* 1995).

Although the land-uses identified as most capable of integration in wetlands were conservation, tourism, recreation, commercial wildlife harvesting and non-intensive pastoralism (Whitehead et al 1990), it is apparent that some government departments see intensification of pastoralism (Lemcke 1996), horticulture and irrigated crops as the highest priority. With our knowledge of *Mimosa*'s invasive potential of open and disturbed areas, such land use practices would only encourage the spread of the weed, thus, hindering the effectiveness and economic value of the aforementioned industries.

The above mentioned impacts of *Mimosa* are not restricted to european land use practices. Aboriginal people have control of approximately 87% of the Northern Territory coastline and thus many of the major sub-coastal wetlands that are threatened by *Mimosa* (Storrs 1998, Storrs *et al* 1999). Aboriginal people continue to be reliant on the natural environment for both their spiritual and physical well being; practices such as hunting and foraging not only provide people with food, but are closely tied to spiritual beliefs and traditional law, and allow each generation to share extensive environmental knowledge with succeeding generations (NLC & eriss 1997). The invasion of weeds physically impedes access to traditional hunting grounds and reduces the availability of wildlife due to loss of native habitat.

Aboriginal interests are also investigating a mixture of land use options, including ecotourism, sustainable commercial wildlife harvest and pastoralism (Rea & Storrs 1999, NLC & eriss1997). Such enterprises would give Aboriginal people economic independence in the long term. The impacts of *Mimosa* on such endeavours, as outlined earlier, threaten this independence (Storrs 1998, Storrs *et al* 1999, NLC & eriss 1997).

Another economic impact of *Mimosa* is the financial cost of controlling the weed itself. Up to 1996/97 it is estimated that $17.8 million has been spent by government and landholders on research and control of *Mimosa*. Projected expenditure for 1997/98 was $2.6 million (Mimosa Management Committee 1998). Despite this cost the Northern Territory remains infested with an estimated 80000 ha of *Mimosa*. However, it is likely that without this expenditure and the subsequent knowledge gained, this area of infestation would be much higher.

6.0 Control measures

The basis of a strategy for individual farms and districts is to prevent initial invasion of the weed, eradication of small infestations by physical or chemical means and, for large infestations, an integrated approach involving biological control, herbicide application, mechanical removal, fire and pasture management. The land use practices and farm sizes where *Mimosa* occurs in Australia, Asia and the United States may be different, but the problems encountered with control and the principles of management are common to all regions.

When formulating control strategies and when implementing control recommendations, it is necessary to understand the biology and ecology of the plant, the seasonal climatic conditions, land use, and herbicide practices which have proved unsatisfactory in the past. Difficulties in controlling *Mimosa* are still encountered today, but can be overcome. A continuing, effective public awareness campaign is essential to obtaining public support and government finance for control programs.

A common problem is often the discontinuity in control. Control programs by private landholders and governments may be interrupted for a variety of reasons such as funding shortages and lack of other resources and equipment. Interruptions in any control project wastes time, resources and funds, and allows the *Mimosa* time to recover from past treatment (Miller et al 1992).

Miller et al (1981) summarised the problems affecting the control measures of *Mimosa* as:

1. Very rapid growth rates of the plant.
2. The ability of the plant to flower and seed all year round.
3. Production of very large quantities of seed.
4. The inherent long term viability of the seeds.
5. Both flood and drought tolerance of the plant.

6. Inaccessibility to isolated plants where other vegetation is thick on the river banks.
7. Inaccessibility to many areas during the wet season, hence the plants could flower and seed during that time and spread further afield.
8. Spread of seed by uncontrolled means such as floodwaters, native and feral animals and man.
9. Low returns per unit area of land, making landholders loath to control the plant on their properties.
10. Lack of intensive agricultural systems which would allow for control of *Mimosa* on properties as an integral part of land preparation operations for crops and improved pastures.

6.1 Prevention

Preventative weed control is the most cost efficient form of weed management and plays an integral role in strategic weed management. When weeds are managed on a catchment basis it is critical to identify weed-free areas and manage those areas to maintain that status. Part of the preventative management of *Mimosa* involves undertaking comprehensive ground and aerial surveys to identify isolated plants before they expand into larger infestations. Preventative management should target smaller infestations on the extremity of known *Mimosa* distributions in an attempt to limit the spread of the total weed population (Ashley 1999).

In addition to seed that is ingested or adheres to the coats of animals, contaminated railroad cars, vehicles, machinery, soil and sand are also responsible for dispersal of *Mimosa* seeds (Miller & Pickering 1983, Napometh 1983). Any vehicles or machinery which come into direct contact with mature *Mimosa* plants may pick up seed. It can lodge in roof guttering, in radiators and other air intake cavities, on belly plates, and in mud and soil adhering to the vehicle. When clearing *Mimosa*, machinery such as bulldozers and tractors are particularly prone to contamination.

The movement of sand and soil for construction or other purposes has resulted in the spread of *Mimosa* seed. For example, in Thailand much of the spread of *Mimosa* can be attributed to the introduction of contaminated sand used for construction purposes. On roadsides, graders and other earth moving equipment may move contaminated soil to new areas. Contaminated materials used for building or road construction in the catchment of a watercourse will usually result in the whole watercourse becoming infested (Benyasut & Pitt 1992).

In Australia, permits for sand removal from known *Mimosa* infested areas on the Adelaide River have not been issued since 1970. This may stop removal of large quantities of sand for commercial use, but it does not stop individuals taking small quantities for small jobs (Miller et al 1981). This is an example of the need for public education and awareness.

A summary of measures to prevent the introduction and spread of *Mimosa* seed is outlined below. (from Benyasut & Pitt 1992):

- Educate the community about the problems caused by *Mimosa* and on the action which should be taken to prevent its introduction and spread.
- Maintain dense ground-cover, to provide competition with germinating and developing *Mimosa*.
- Only purchase clean stock feed, and clean crop and pasture seed for planting.

- Prevent entry into infested areas and thoroughly clean vehicles and machinery before moving from infested areas.
- Wash down livestock from infested areas and hold them for at least 48 hours before introducing them to clean areas.
- Do not use or move sand or soil from infested areas.
- Control *Mimosa* growing upstream of clean areas.
- Control mature and juvenile *Mimosa* before seeding.
- Keep *Mimosa* away from roads, railways and access points. If possible, keep it away from water.

Obviously, preventative measures in the NT for the initial spread from The Botanic Gardens, upper Adelaide River and then on to other catchments, came too late. Since then, they have most likely been successful in preventing further spread in many areas.

6.2 Physical and mechanical control

Physical and mechanical methods of weed control have been used since very early times and still have application for *Mimosa*. Theses methods have been described by Siriworakul & Schultz (1992). They can be applied using relatively unskilled labour and use equipment which is often readily available. These methods are usually considered as temporary control options for large infestations of *Mimosa,* and their success, if used alone, are very limited. Physical and mechanical methods of control are usually employed in combination with herbicide application and burning (Miller 1988, Miller et al 1992, Miller & Lonsdale 1992), and can be an effective means for preventing or slowing the spread of *M. pigra* by controlling satellite outbreaks from major infestations (Cook *et al* 1996). When using these control methods for *M pigra*, the large soil seed population (Lonsdale *et al* 1988) and the ability to resprout vigorously from stumps (Wanichanantakul & Chinawong 1979) means that rigorous follow up control, sometimes for as long as 10 to 15 years (Cook et al 1996, Miller et al 1981) has to be maintained for some years after the eradication of mature plants.

The environmental impacts of these methods are not usually considered to be great. Physical removal of isolated plants by hand does not disturb or pollute the surrounding environment. If large machinery is being used on a large dense infestation it is most likely that there is little native understory left anyway. If there is some native understory or even some emergent natives, then these will most likely be destroyed. In most cases, native plants or other competitive pastures would need to be sown and nurtured (see Ecological control, below).

6.2.1 Hand weeding

Hand weeding is usually employed on small plants or seedlings and can be very effective for isolated plants, however it is difficult and time consuming when the plants are large. Hand weeding is suitable for controlling seedlings amongst crops, but may not be practicable when they are present in large numbers. Any seed should be collected first and burnt in a container. The branches should then be cut off and the roots removed prior to allowing the plant to dry before burning. It is important that no portion of the plant should be dropped onto wet soil or into water as they are able to take root. It is possible to hand-pull large plants growing in water, as under these conditions the tap root becomes rotten and the plant feeds from its adventitious roots. Strong gloves are required for the hand-pulling of *Mimosa* as the plant is covered with prickles.

6.2.2 Hand implements

Hand hoeing or grubbing with a mattock is faster, more efficient and can remove seedlings more effectively than pulling by hand. It is important to remove all roots. Long handled cutters, axes and machetes may be used to cut down plants, however, as mentioned earlier, the plants quickly regrow from the stumps, thus the control is only temporary. Regrowth may be prevented by immediate application of an appropriate herbicide (see Chemical control, below). In flood-prone areas *Mimosa* plants should be cut before flooding occurs as the remaining stumps will die if submerged for more than 30 days (Thamasara 1985). Cutting plants before flooding has been successful in controlling *Mimosa* in reservoirs in Thailand (Thamasara 1983).

6.2.3 Power operated equipment

In cultivated areas young seedlings can be controlled by rotary-hoeing and ploughing. Blade type tool bars are better than ridgers or tyned machines for this work. Animal power can be used for cultivation and to pull out large isolated plants for later burning. Tractor power allows for large areas to be controlled. Slashing or mowing can reduce the height and visibility of *Mimosa*, however, a heavy duty slasher is needed and the *Mimosa* will regrow. Continued slashing allows other species to compete with *Mimosa*.

Motorised brush cutters and chainsaws are more efficient than hand implements for cutting down larger plants. Heavy duty, modified machines are recommended for *Mimosa* work

Large tractors and bulldozers have been used with a variety of implements including rollers, chains and discs that will knock down *Mimosa,* but re-growth from stems, seed and roots will occur. These methods are best used in combination with herbicide application, and for preparation of areas prior to burning and crop or pasture planting. The use of chains between two bulldozers can cover a considerably greater area in large infestations. The chain used for the Oenpelli site, in western Arnhem Land, was 100 metres of 75mm chain weighing 6500kg (DPI&F 1996). Bulldozers tend to lay the plant flat but the "whipstick" nature of *Mimosa* allows many plants to stand up after one pass of a bulldozer.

6.3 Ecological control

The use of fire and competitive pastures to control *Mimosa* has been described by Miller and Lonsdale (1992) and Miller (1992b).

6.3.1 Fire

The use of fire as a control mechanism on *Mimosa* thickets is limited because of their low flammability. Denser thickets will not usually support a fire due to the lack of understory fuel. When infestations are burnt, fire does not have a major impact on mature plants, although this can vary depending on the season and weather conditions. In one study only about 10% of mature pants were killed (Miller 1988). Mature plants will reshoot quickly, most likely from dormant buds in the base of the stems. Mortality in seedlings is greater but they too are resistant with more than 50% regrowing after fire. If *Mimosa* is first stressed with herbicides, or is burnt when at the end of the dry-season when the plants are drought stressed, the mortality is increased (Miller *et al* 1981). Ignition of *Mimosa* with gelled gasoline applied from an aircraft can increase the flammability, resulting in a hotter fire and more damage to the *Mimosa* (Miller & Lonsdale 1990, Miller 1991b).

Fire can have varying affects on *Mimosa* seed, depending on the fuel load and the position of the seed in the soil profile. Fire results in a higher level of seed germination on the soil surface, by scarifying the hard seed coat. Some of the seed on the surface is killed by fire.

Beneath the soil surface there is only a small rise in temperature, the effect penetrating to about 5 cm.

Fire does have a role in integrated control programs by enhancing the kill of plants that have not been completely killed by herbicides, to break seed dormancy, to kill seeds and to clean up sprayed areas.

An environmental impact of using fire as a control method could be the loss of any native vegetation if it were not suitably adapted to fire. Another problem with the use of fire is the potential to kill any biological agents present. For a temperate Australian weed, the timing of fire was found to determine whether biocontrol agents died or increased markedly in number (Briese 1996). Biocontrol agents could possibly

6.3.2 Competitive Pastures

Competitive pastures were first investigated in the upper Adelaide River area in the 1970s. On the floodplains, the dominance of *Mimosa* was probably facilitated by overgrazing by feral water buffalo and removal of the floodplain flora by fire (Lonsdale *et al* 1989). The sowing of pasture species to compete with *Mimosa* seedlings may therefore assist in its control.

Mimosa seedlings are susceptible to competition from grasses. Pot trials showed that the stem diameter, number of leaflets and leaves, dry weight per unit of height and dry matter yield were reduced by the presence of Koronivia grass (*Brachiaria humidicola*) (Miller 1988, Miller 1992a). The earlier trials used Calopo (*Calopogonium mucunoides*), however, this species was not suitable for seasonally flooded black, cracking, clay soils of the sub-coastal plain where *Mimosa* is most dominant.

Control of dense, mature *Mimosa* using competitive pastures alone is unlikely because of its size and the lack of light penetration to the ground. The use of pastures is a logical sequence to the application of herbicides, mechanical control and burning. The *Mimosa* canopy can be opened up to allow either natural regeneration of native species or the sowing of other species to compete with *Mimosa* seedlings (Miller 1988). Effective biocontrol agents may also result in opening the *Mimosa* canopy.

Many *Mimosa* infestations are in or near to permanent water bodies, under the canopy of trees in swamps with little natural understory and in tidal river margins which are flooded daily. The sowing of pastures into such situations is not possible.

Provided the competitive pasture is a native or not a potential weed, there should be no adverse environmental impacts of using competitive species. There are many introduced species which may be suitable as competitive pastures on floodplains outside conservation areas. In northern Australia, the native grasses *Hymenachne acutigluma* and *Oryza australiensis* have been identified as potential *Mimosa* competitors.

6.4 Chemical Control

6.4.1 Herbicides used for control of mimosa

The use of herbicides to control *Mimosa* has been described by Miller (1988) and Miller and Siriworakul (1992).

Nineteen herbicides have been tested in the Northern Territory and Thailand for control of *Mimosa* (table 1). The aim was to find herbicides which could replace 2,4,5-T, which was the main herbicide used in the 1960s and '70s. Use of 2,4,5-T required repeated applications because of regrowth from the seed bank in the soil. Also in the mid 1970s and '80s there was much controversy on public health aspects of its use (Miller *et al* 1981). Further aims were to test soil residual herbicides, to refine rates of application and methods of application for different land management systems, and to measure seasonal effects on herbicide efficacy (Harley *et al* 1985, Miller 1988).

The most appropriate herbicide and method of application to use on *Mimosa* will depend on the formulation, mode of action, selectivity, rain-fastness, cost-effectiveness, residual nature, safety and toxicity. Other factors include location, season, growth stage of the plant, density and accessibility of an infestation, land use, soil type, and the availability of labour (Miller 1988, Miller & Siriworakul 1992, Siriworakul & Pitt).

The long term seed viability and large seed bank in the soil emphasise the importance of regular follow-up control when using herbicides which do not have a residual action (Miller 1988).

Table 1 Herbicides and methods of application evaluated for the control of *Mimosa pigra* in Australia and Thailand (from Miller & Siriworakul 1992).

	Method of application					
Herbicide	**Soil**	**Cut stump**	**Stem injection**	**Basal bark**	**Foliar - Ground**	**Foliar - Air**
Atrazine					*	
Clopyalrid					*	*
Dicamba	*	*	*	*	*	*
Dicamba + MCPA					*	*
Ethidimuron	*					
Fluroxypyr					*	*
Fosamine					*	
Glyphosate		*	*		*	
Hexazinone	*	*	*		*	
Imazapyr		*			*	
Karbutilate	*					
Metsulfuron methyl					*	*
Picloram + 2,4-D			*	*	*	
Picloram + 2,4-D + triclopyr			*	*		
Picloram + 2,4,5-T		*	*	*		
Picloram + triclopyr		*	*	*	*	*
2,4,5-T					*	
Tebuthiuron	*					
Triclopyr		*	*	*	*	

Five of the chemicals that are commonly used today and are the basis of the program to control *Mimosa* on Aboriginal land in the Northern Territory by chemical and mechanical methods, are briefly described below. The trade name of the product used appears in parentheses:

1. Tebuthiuron (Graslan®)

A pelletised formulation which is very easy to apply to both by air and on the ground, and has minimal risk of drift problems and great application accuracy. The chemical is selective for woody plants and at standard application rates little damage occurs to grasses and sedges. Its residual activity controls subsequent germinations of *Mimosa* throughout the wet season.

2. Fluroxypyr (Starane®)

This liquid herbicide can be applied throughout the wet season as it is very quick acting and has a rain fastness period of about one hour. It is also selective for woody plants and broad leaf species.

3. Dicamba (Banvel®)

A liquid herbicide which can be sprayed with safety near palms and potable water bodies. It is generally used as a selective post-emergent herbicide for controlling broad leaf weeds, but at the recommended rates affects *Mimosa*.

4. Metsulfuron methyl (Brushoff®)

A dry flowable formulation that is selective against woody plants and broad leafed species where it affects a particular enzyme found only in certain plants. Because it is mixed with water before application, the small quantities of active ingredient required make transport to remote sites simpler. In an emergency, Metsulfuron packets can be ditched and recovered without damage to the environment, a feature not possible with liquid formulations. It has been shown to work effectively in the wet season.

5. Hexazinone (Velpar®)

This is applied on the *Mimosa* stump after cutting or on the surrounding soil and is very useful for ground applications, but it is non-selective and best suited to individual application by spot gun.

Some of the features of the five herbicides are shown in table 2.

Table 2 Features of the five major herbicides

Chemical	Proposed max rate g/ha a.i.	Mimosa Mortality [1]	Control of regrowth [2]	Residual activity [3]	Toxicity [4]	Selectivity [5]	Ease of use [6]
Tebuthiuron	2000	H	H	H	M	H	H
Fluroxypyr	600	M	H	L	M	M	M
Hexazinone	0.8	H	H	M	M	L	M
Metsulfuron	45	H	H	L	L	H	M
Dicamba	1200	L	M	L	M	H	M

1 *Mimosa* mortality assuming optimal conditions: H ≥ 98%; M = 90–98%; L = 70–90%.

2 Regrowth control assuming typical wetland conditions: H = > 6 months; M = 3–6 months; L ≤ 3 months.

3 Residual activity of herbicide assuming typical wetland conditions: H = > 6 months; M = 3–6 months; L ≤ 3 months.

4 Toxicity based on mammalian toxicity (LD50 mg/kg): M = slightly toxic (500–5000); L = practically non-toxic (5000–15000).

5 Selectivity of herbicide: H = highly selective; M = moderately selective; L = not selective.

[6] Ease of use: H = very easy to use; M = easy to use; L = moderately difficult to use.

Soil applied herbicides

The herbicide used for soil application from the air is tebuthiuron. The herbicides recommended for soil application from the ground are ethidimuron, hexazinone and tebuthiuron. Ethidimuron and hexazinone are less selective than tebuthiuron. Factors that effect the efficacy of soil applied herbicides include; differences in soil profile characteristics, soil texture, the type and amount of understory vegetation, soil organic matter, rainfall distribution, the size of the plants and their root distribution.

All of these soil-applied herbicides have reduced activity in soils with high clay content such as the heavy black clay soils of the sub-coastal plains. These soils typically have poor internal drainage so it is possible that the herbicides may not leach down to the root zone of mature plants. The higher clay content can also result in greater herbicide adsorption to the soil particles. In most cases the efficacy of the herbicide can be improved by increasing the application rate. These herbicides have the advantage of residual properties that may be from several months to several years depending on the conditions, thus in some cases there will be continuing seedling mortality.

Foliar applied herbicides

The three herbicides recommended for foliar aerial application are dicamba, fluroxypyr and metsufuron methyl. The factors that effect the results of aerial spraying include; temperature, humidity, evaporation rate, horizontal and vertical air movement, droplet size, aircraft speed and height above the target. The five herbicides recommended for foliar ground application are dicamba, fluroxypyr, glyphosate, metsulfuron methyl and picloram + 2,4-D.

Cut stump applied herbicides

The herbicides recommended for this method are dicamba, glyphosate, hexazinone, imazapyr and triclopyr. Miller *et al* 1989 concluded that dicamba was the most cost-effective herbicide for cut-stump application. Mimosa control personnel working in the field generally use a mixture of Starane® (fluroxypyr) and diesel sprayed onto the cut stump (Salau 1992,1993,1997).

Stem injection applied herbicides

Stem injection trials in the Northern Territory show that only hexazinone and dicamba were effective in producing high levels of kill in *Mimosa*, and that effective kills in both wet and dry seasons were obtained only with the concentrated products. The traditionally used herbicides, 2,4,5-T + picloram, triclopyr and glyphosate are known to be active by stem injection on other woody plants, but were less effective on *Mimosa*. The most cost effective herbicide for stem injection application was found to be dicamba (Miller & Pitt 1989).

Basal bark applied herbicides

The most common herbicide associated with basal bark spraying was picloram + 2,4,5-T. Because of the controversy over the safety of 2,4,5-T, its use has been banned in some countries. In northern Thailand, basal bark application trials were conducted using triclopyr, picloram + 2,4-D, tryclopyr + picloram + 2,4-D and dicamba. High kills were obtained with triclopyr, tryclopyr + picloram + 2,4-D, triclopyr + picloram, and dicamba mixed in water, demonstrating that the aqueous herbicide solutions are capable of penetrating the bark of *Mimosa*. This would lead to an economic advantage by reducing the amount of diesel required (Thamasara *et al* 1988). Reports from field personnel suggest that, as for the cut-stump method, Starane® (fluroxypyr) mixed with diesel (1:50 mixture) is commonly used (Ashley 1999).

6.4.2 Application methods and rates

Herbicides can be applied by a number of different techniques. Those most commonly used in northern Australia and Thailand (Miller 1988; Siriworakul & Pitt 1992) are described below.

Mimosa has a peak flowering and seeding period in the mid to late wet season (Lonsdale 1988, Miller 1988). Thus, the most effective time to apply herbicides is during the period of active growth (for herbicides whose translocation is reduced by inactive growth) and before the plants have produced mature seed, in order to reduce the plant population the following year.

Due to the height, density and prickly nature of *Mimosa*, which makes ground access to most *Mimosa* infestations difficult, the most practical method of applying herbicides to large infestations is from aircraft. The main disadvantages of aerial application of foliar herbicides are the potential for herbicide drift to off-target species and contamination of the environment (eg into waterways). The application of pelletised and granulated herbicides can greatly reduce problem of drift. The problem of drift with liquid herbicides can be minimised by applying the herbicides during favourable climatic conditions such as high humidity, lower temperatures and wind speed (Miller 1988). When spraying during times of moisture stress or immediately after rain the leaves may be closed, thus the plant presents a smaller receptive leaf area to the herbicide. The leaves may also close due to aircraft air turbulence from low-level aerial spraying.

The ground methods of Cut stump, stem injection and basal bark applications where the herbicide is applied directly onto the plant have the advantage of minimising off-target damage and environmental contamination (Harley *et al* 1985, Thamasara *et al* 1985, Miller & Pitt 1989, Miller *et al* 1989). The other ground methods of foliar spraying and soil application of both liquid and pelletised herbicides can still pose some risk to off-target species and the environment if proper care is not taken. Particularly in hot and windy conditions, foliar sprays can drift to off-target species. A light breeze is ideal for minimising drift and obtaining good coverage. Depending on its rainfastness, the herbicide may be washed off the foliage if foliar application is carried out immediately prior to rainfall. Soil applied herbicides are usually safe provided they are accurately applied and care is taken on sloping ground and near waterways, as they may be carried by runoff following rainfall (Siriworakul & Pitt 1992).

Foliar application - from the air

Aerial foliar application is by fixed wing aircraft or helicopter. Helicopters have the advantage of better visibility, no need for formed airstrips, a slower airspeed and a greater swath (DPI&F 1992). Larger infestations need to be aerially mapped and marked on the ground to assist in the aerial application of herbicides. The effects of evaporation and drift of liquid herbicides can be reduced by using nozzles which produce large droplets. However, the selection of droplet size must be a compromise between obtaining minimal drift and providing adequate numbers of droplets for good coverage of the weed (Yates 1981).

In the Northern Territory nozzles which produce droplets with the volume median diameter of 360-410 microns are used. Best results are achieved when foliar spraying is done in the mid wet season with conditions of complete cloud cover, high humidity and low evaporation. Low relative humidity can cause losses of herbicide by evaporation in the air before reaching the plant or from the leaf surface, and poor absorption due to effects on stomatal behaviour.

Foliar application - from the ground

As for aerial spraying, the best results are achieved in the wet season due to environmental conditions and the condition of the plant itself. High volume handguns are best suited for foliar treatment of isolated plants of any size, clumps or small infestations and the plants are sprayed to the point of runoff. A droplet size of 100-300 microns produces more misting and better coverage.

Soil application - from the air

Using this method it is possible to cover large *Mimosa* infestations with less drift than when using liquid foliar herbicides. Earlier aerial applications of Graslan® pellets resulted in striping, where straight lines of untreated or subtreated *Mimosa* were left (DPI&F 1996). It is thought that this may be caused by insufficient calibration of the application equipment to compensate for changes in humidity, windspeed, wind direction and the closeness of the adjacent flight paths, and that the problem may be overcome by daily on ground calibration of pellet distribution and more on ground marking (Lonsdale 1992b).

The soil-applied herbicides rely on rainfall to incorporate the active constituent into the soil where it is taken up by the roots of the target species. Thus, the timing of application is critical. For tebuthiuron it is acknowledged that it be applied before the floodplains become too wet and the soil is too waterlogged to accept it or it dissolves into surface water where it is ineffective or subject to runoff. It was originally thought that application of tebuthiuron after the first rains of the wet season had closed the cracks in soils would prevent the loss of pellets down the cracks. It has subsequently been shown that that there is no advantage to applying tebuthiuron to sealed soil.

Soil application - from the ground

When using herbicides such as tebuthiuron that require even distribution, large individual plants will require enough treatment to ensure that the feeder (secondary) root system is covered. It is worth noting that in the Northern Territory the feeder root system diameter has been measured at 4.4 m, thus requiring a herbicide coverage of approximately 16 m^2, whereas in Thailand, the feeder root system diameter has been measured at over 7 m.

Cut-stump application

As mentioned earlier, cutting of the stems of *Mimosa* will only result in regrowth of the plant. If seeds are near to maturity, cutting the stems will immediately prevent their maturation. The cut-stump method of control involves the application of herbicides to the cut stump and is practical for control of small infestations, scattered juveniles with thick enough stems, or mature plants. Dense infestations may be treated in this way where sufficient labour is available. It is also useful when foliar application may affect nearby crops and when the potential for herbicides entering the soil or aquatic systems is a problem.

Studies have shown that the most effective kills are achieved when this method is used in the wet season and when the herbicide is applied immediately after cutting the stump. The stems are cut 10-30 cm above the ground with lopping shears, machetes or motorised saws, depending on the size of the plant. A horizontal cut helps prevent herbicide runoff and maximise absorption. The herbicide is applied at 0.5 ml of solution per centimetre of stem diameter, using a spot gun or knapsack sprayer. As the stems are manually removed, access to the infestation is improved and competition with desirable species is reduced.

Stem-injection

The method involves cutting a 'pocket' into the stem as close to the base as possible using a small axe or machete, and applying the herbicide to the pocket with a spot gun. Specialised tree injectors are made for this purpose and their use involves stabbing the tree at an angle of 45-60° near the base of the plant, then levering the injector downward, thus creating the pocket. The injector then applies the dose of herbicide.

The amount of herbicide is 0.75-1.5 ml depending on the size and number of stems. In the trials, stems with a circumference up to 300 mm received the single 0.75 ml dose, while those with a circumference of 301-600 mm received two doses. Where trees had multiple stems at or near the base, each stem was treated so that the actual volume of herbicide applied per plant varied. This method is best suited to treatment of mature plants in scattered to moderate infestations where sufficient labour is available. Dense infestations have insufficient access, while seedlings or thin stemmed plants cannot be treated with this method.

Basal bark application

The basal bark application of herbicides involves applying a translocatable herbicide solution to *Mimosa* stems at least 30 cm from ground level. The herbicide is applied with a modified spot gun or knapsack sprayer. The herbicide is usually in a lipid soluble form (eg ester) and mixed with an oil carrier such as diesel. Each stem must be sprayed to the point of runoff on all sides. Approximately 10-30 ml of herbicide solution is required for each stem. The effects of basal bark spraying of *Mimosa* are more rapid in the wet season than in the dry season.

Less herbicide is required than with an overall foliar spray, less time is required to apply it and tall plants can be treated relatively easily provided there is access to the lower trunk. As for the stem injection method, basal bark spraying is best suited for scattered to moderate infestations where sufficient labour is available. Access will be prevented in dense infestations and it is not recommended to treat seedlings in this way.

Table 3 shows the recommended herbicides and methods of application for control of *Mimosa* in different land-use situations in Australia and Thailand.

Table 3 The recommended herbicides and methods of application for control of *Mimosa pigra* in different land-use situations in Australia and Thailand.

Active Ingredient in Herbicide	Method of Application	Rate of Product	Situation
AUSTRALIA			
Dicamba as the dimethylamine salt	Foliar spot spray	1% v/v	Town areas, pastoral areas, roadsides and water reservoirs
(200 g/l)	aerial spray	6 l/ha	
	cut stump	50% v/v, 0.5ml/cm stem diameter	
	stem injection	conc. 1 x 0.75ml for stems < 30 cm circ	
		conc. 2 x 0.75ml for stems > 30 cm circ	
Ethidimuron (700 g/kg)	soil spot spray	0.5% w/v	Isolated plants in pastoral areas and roadsides
	soil application	10 kg/ha	
Fluroxypyr as the methyl heptyl ester (300 g/l)	foliar spot spray	0.5% v/v	Pastoral areas and roadsides
	aerial spray	1.5 - 2 l/ha	
Glyphosate as the isopropylamine salt (360 g/l)	foliar spot spray	1% v/v	Town areas
Hexazinone liquid (250 g/l)	soil application	4 ml conc/plant	Isolated plants in pastoral areas and roadsides
	cut stump	or 4 ml/m^2 in grid pattern	
	stem injection	50% v/v, 0.5 ml/cm stem diameter	
		conc. 1 x 0.75ml for stems < 30 cm circ	
		conc. 2 x 0.75ml for stems > 30 cm circ	
Metsulfuron methyl (600 g/kg)	aerial spray	60 - 75 g/ha	Pastoral areas
Tebuthiuron (200 g/kg)	aerial application to soil	7.5 kg/ha	Pastoral areas
	hand application to soil	1 g/m^2	
Triclopyr as the butoxyethanol ester (480 g/l)	wet season basal bark	2% in diesel	Isolated plants in pastoral areas

Table 3 continued

Active Ingredient in Herbicide	Method of Application	Rate of Product	Situation
THAILAND			
Dicamba as the dimethylamine salt	foliar spray	0.75 - 1.5% v/v or 4.7 - 9.4 l/ha	Roadsides, canals if water depth > 1m, and non agricultural areas
(480 g/l)	cut stump	10 - 20%, 1 - 2 ml/stump	
Dicamba + 2,4-D as the dimethylamine salt (310 g/l)	foliar spray	0.8 - 1.0% v/v or 4.84 - 6.45 l/ha	Roadsides, canals if water depth > 1m, and non agricultural areas
Fluroxypyr as the methyl heptyl ester (200 g/l)	foliar spray	0.3 - 0.4% v/v or 1.88 - 2.5 l/ha	Roadsides, canals if water depth > 1m, and non agricultural areas
Glyphosate as the isopropylamine salt (360 g/l)	foliar spray	0.75 - 1.5% v/v or 4.7 - 9.4 l/ha 10 - 20% v/v, 1 - 2 ml/stump	Beside canals, roadsides, in water reservoirs and in agricultural areas before cropping or after harvest
Heaxazinone granules (200 g/kg)	soil application	10 kg/ha	Non agricultural areas
Imazapyr (100g/l)	cut stump	25% v/v, 1 - 2 ml/stump	Any situation
Metsulfuron methyl (600 g/kg)	foliar spray	100 - 133 g/ha	Roadsides, canals if water depth > 1m, and non agricultural areas
Picloram + 2,4-D as the tri-isopropanol amine salt (305 g/l)	foliar spray	1.0 - 1.5% v/v or 6.25 - 9.4 l/ha	Roadsides, canals if water depth > 1m, and non agricultural areas
Tebuthiuron (200 g/kg)	soil application	10 kg/ha	Non agricultural areas
Triclopyr as the butoxyethanol ester (480 g/l)	cut stump	10% v/v, 1- 2 ml/stump	Any situation

6.4.3 Effectiveness of control methods

The most well documented application of herbicides for the control of *Mimosa* in the Northern Territory has been on the infestation at Oenpelli under the five year program to Control *Mimosa* on Aboriginal lands by chemical and mechanical methods. This provides an ideal test case to discuss the success of a major chemical control program.

The Oenpelli program was the largest single aerial herbicide application to *Mimosa* in the world, with over 60 tonnes of chemical applied to the wetland over 5 years (Storrs 1999). The total amount of Graslan®, including ground application, applied to the 7000 ha is more than 100 tonnes (*Mimosa* Steering Committee 1996). On the face of it, the program was successful at destroying 7000 ha of *Mimosa*. However the success of the program is dependent on a continuation of ground control activities similar to those successfully employed for some years in Kakadu National Park (Storrs 1999).

A report by an independent consultant, Australian Research Associates in conjunction with AACM International (Australian Research Associates 1995) concluded that:

- the program has clearly been effective on target infestations;
- the program has been efficient to the extent that major reductions in infestation areas have occurred and there is no objective evidence to suggest any known alternatives were reasonably available to the Committee over the period (other than any which might be identifiable in hindsight);
- it is axiomatic, however, that if on-going post-*Mimosa* Steering Committee actions are not at least sufficient to maintain the status quo in place at the end of the program, the entire program will have been a regrettable waste of resources;
- there were undoubtedly problems associated with the 'learning curve'; in undertaking such a large program with no comparable role model, some aspects of the program, in particular data management, could have been better controlled.

The *Mimosa* control program in Kakadu National Park (KNP) is a test case for the success of ground control methods in the right circumstances. The program has successfully prevented the establishment of *Mimosa* in 1900 km^2 of suitable wetland habitat. The strategy employed has been one of searching for and destroying all outbreaks, and rigorous follow-up in subsequent years (Cook et al in press). Records kept by the control teams showed that the density of outbreaks in KNP increased with proximity to large infestations to the east and west of KNP. Since systematic control in KNP started in 1984, these infestations outside of the park have grown to cover thousands of hectares, with the stand at Oenpelli doubling every 1.4 years through the 1980s. Clearly, this rigorous campaign against *Mimosa* in KNP has prevented these World Heritage wetlands suffering the same fate (*Mimosa* Steering Committee 1996). This demonstrates the benefits of 'getting in early', as the ground control teams would have had little effect on a 7000 ha infestation such as that at Oenpelli.

6.4.4 Monitoring and impacts of herbicides

Considering the large amounts of herbicides, particularly tebuthiuron (Graslan®), used in northern Australia for *Mimosa* control, it was imperative that an assessment of the sensitivity of local aquatic organisms to such chemicals be performed. Such an assessment was carried out for the herbicide, tebuthiuron (Camilleri et al 1998). While no data existed on the aquatic toxicity of tebuthiuron to Australian tropical freshwater species, its effects on northern hemisphere temperate species had been extensively studied. The studies indicated that tebuthiuron toxicity to aquatic animals was very low compared to aquatic plants.

Camilleri et al (1998) reported that tebuthiuron was not particularly toxic to the three non-target Australian tropical freshwater organisms assessed in the present study:

- The purple spotted gudgeon, *Mogurnda mogurnda*
- The green hydra, *Hydra viridissima*
- the cladoceran, *Moinodaphnia macleayi*

However, as expected, further studies on the sensitivity of two local aquatic macrophytes (the green alga, *Chlorella* sp. and the duckweed, *Lemna aequinoctialis*) have demonstrated much greater sensitivity to tebuthiuron. Adverse effects were observed in the laboratory at tebuthiuron concentrations well below those measured in water and suspended sediment following the large scale treatment of *Mimosa* on the Oenpelli floodplain. A quantitative ecological risk assessment of tebuthiuron in northern Australian wetlands is currently being completed, and it is considered essential that similar assessments be carried out for the other major herbicides used to control *Mimosa*.

The monitoring program associated with the control of *Mimosa* on the Oenpelli floodplain revealed no environmental impacts outside the control area. It has taken about five years since the first herbicide application for satisfactory recovery of native vegetation. Attempts to artificially assist revegetation by sowing of seed and planting of vegetative material have largely failed, but also proved unnecessary.

Some stands of melaleuca trees (4 km^2) which had *Mimosa* growing beneath were destroyed by herbicide application and some areas of scalded soils persist in the floodplain margins. Recruitment of new stands of *Melaleuca* has occurred episodically, and in several areas, new stands of one to five hectares have established within the last five to seven years. It appears therefore, that given particular conditions, *Melaleuca* woodlands will return unaided. In other relatively small areas on the margins, there are no signs of vegetation recovery following *Mimosa* control. These areas may have suffered from over-application of Graslan, or possibly from the development of secondary salinity as a consequence of prolonged periods without extant vegetation. The problems that led to uneven distribution of herbicides have been corrected. It is highly unlikely that similar problems will occur in the future (Cook 1993,1994,1996).

In 1995/96, metsulfuron methyl (Brushoff® and Generex®) was used because its price had fallen and the supply of Starane® was limited. This was the first time a large amount of metsulfuron methyl had been applied to a floodplain situation. As well as controlling *Mimosa*, it caused significant damage to *Eleocharis* spp., the dominant sedge on the Oenpelli floodplains (DPI&F 1996).

6.5 Biological control

If it is possible to eradicate a new outbreak of *Mimosa* by physical or chemical means, then this should be attempted first. The features outlined earlier that combine to make *Mimosa* such a successful weed mean that total eradication using these methods is unlikely in the Northern Territory. There would be an on going requirement to check for new outbreaks and recolonisation of existing infested areas. Biological control involves the establishment of host-specific natural enemies of the weed to reduce its competitive edge (van Rangelrooy 1994).

For biological control research, it takes 10 or more years before results become apparent. When integrated with the strategic use of other control techniques, biological control gives the highest probability of successful, cost-effective weed management in the long term. Given their high initial costs, biological control programs are only undertaken for weeds that are a major problem over large areas (Mimosa Steering Committee 1996).

Mimosa does present a very different picture in its native range. This is either due to difference in environmental conditions or, to the more than 200 species of insects and several fungi that attack *Mimosa*. It has been suggested that that physical conditions are largely responsible for *Mimosa*'s exceptional growth and therefore that biocontrol may only be part of the solution (Rea 1998).

In 1979, a biological control program was initiated involving the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Entomology and the (then) Northern Territory Department of Primary Production, (now) the NT Department of Primary Industries and Fisheries DPI&F.

CSIRO operates a small station in Mexico to collect biological control agents and a quarantine facility in Brisbane to screen insects for release in Australia. Through plant and insect ecological studies, the impact of these biological control agents is being evaluated. These studies, which are integrated with the Biological Control Program of the Northern Territory Department of Primary Industry and Fisheries, are presently supported by Federal Environment funds.

To date, eleven species of agents have been released against *Mimosa*, these include nine species of insects and two species of pathogenic fungi. All have established in the field except for the most recently released seed-feeding insects, S*ibinia fastigiata* and *Chalcodermus serripes*, for which it is too early to confirm establishment. The four species of seed feeders were selected because they attack seed at different stages of maturity: young green seed, old green seed and hard seed. Although the agents released collectively damage vegetative and reproductive parts of the plant, mature leaves and roots are still largely undamaged, although they are heavily attacked by insects in the native range. Selection of further biological control agents is focusing on those that attack these plant parts. Many species of leaf feeding Lepidoptera are also being assessed, as are leaf beetles whose larvae feed on the roots of *Mimosa*.

The flower-feeder, *Coelocephalapion pigrae* and the stem-borer *Neurostrota gunniella* are widely established over the entire *Mimosa* infestation and field experiments are being carried out to evaluate the impact of these and other insect agents on *Mimosa*. Culturing procedures for the rust, *Diabole cubensis*, which does best in cool, dry conditions, have been refined and the rust will be released at a number of sites in the near future. Aerial application of the fungus, *Phloeospora mimosae-pigrae*, by the Department of Primary Industry and Fisheries resulted in more than 2000 litres being applied to *Mimosa* in the Finniss and Adelaide River systems. The method of application has been refined and the fungus appears to have established.

A computer model based on the known ecology of the weed is being developed, to allow the consequences of different management options to be tested. The model is currently undergoing sensitivity analysis. Through ACIAR supported projects, the biological control research has been extended to Thailand, Malaysia, Indonesia, and Vietnam, which have increasing problems with *Mimosa* (CSIRO 1999a).

The *Mimosa pigra* project has provided a model system for research into improved techniques for host range testing and for predicting and managing the establishment and impact of biological control agents (CSIRO 1999b).

6.6 Integrated control

As the name suggests, integrated control involves utilising a variety of control methods at a particular infestation site in an integrated manner. Integrated control is successful because it accumulates the benefits of individual control techniques, and decreases the probability of *Mimosa* developing resistance to a particular control technique. A typical integrated control program would include appropriate survey and mapping, chemical control, mechanical control, and burning (Ashley 1999).

The *Mimosa* canopy should be opened by treating with herbicides in the wet season, followed by burning in the dry season and planting of pastures in the next wet season. This should suppress the regeneration of *Mimosa*. Mechanical chaining and rolling of dead stems to compact the fuel, may assist burning. The area should then be protected from grazing and fire for at least one year to allow the pasture to establish. Any regenerating plants should be spot treated and when livestock are introduced, grazing pressures should be closely monitored (Miller 1992b).

For a temperate Australian weed, the timing of fire was found to determine whether biocontrol agents died or increased markedly in number (Briese 1996), information which led to more efficacious and integrated weed control. For *Mimosa*, the NT Government (1995, 1997) suggest that resources be directed to integrated control and containment. Studies on the timing and location of control methods that result in maximum impact are required to meet this recommendation. Future research should focus on how one method pre-disposes *Mimosa* to greater damage from another method. While some methods are considered mutually exclusive (eg chemical and biocontrol), others (mechanical control and fire) are hypothesised to predispose *Mimosa* to more damage from biocontrol. Equivalent roles for mechanical, fire and biocontrol is recommended with chemicals playing an operative role in the integrated program (Rea & Storrs 1999).

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