# Reviews

## The Biology of Australian Weeds
## 29. *Acacia nilotica* ssp. *indica* (Benth.) Brenan

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### Name

*Acacia* is the Latinized form of the Greek name (*akakia*) for a prickly shrub growing in Egypt and is derived from *akiz*, a sharp point, and the Malayan word (*kachu*) for the tannin based material obtained from boiling the heartwood of the tree (Parsons and Cuthbertson 1992). The name *nilotica* is Graeco-Latin for 'native of the Nile', referring to the fact that Linnaeus, who first described the species, obtained his specimens from Egypt, whilst *indica* denotes that the native range of the subspecies is the Indian subcontinent. *Acacia* belongs to the family Leguminosae along with about 600 other genera, which include *Mimosa* and *Prosopis*. The Mimosoidea are characterized by their regular flowers and their petals which are valvate in bud and often united at the base. The tribe Acacieae in which *Acacia* is placed has a valvate calyx lobe and indefinitely numerous free stamens. The genus *Acacia* contains around 1200 species (Ross 1981). The common name for *Acacia nilotica* (L.) Del. in Australia is prickly acacia, which is also used for *Acacia paradoxa* DC. Alternative names are blackthorn and lekkerruikpeul (South Africa) and babul and gum-arabic tree (India) (Parsons and Cuthbertson 1992).

### Description

The description below was compiled from Kleinschmidt and Johnson (1979), Ross (1979), Brenan (1983), Tybirk (1989) and Parsons and Cuthbertson (1992).

A small shrub or spreading tree to 10 m high, reproducing only by seed, but capable of regenerating from the stump. Spiny when young and on young stems when mature. Prickly acacia seedlings conform to the Type 2a seedlings of de Vogel (1980) and have an elongated, epigeal hypocotyl. At the base of the hypocotyl is a collar and the cotyledons are borne above soil level. Acacia seedlings are slender and the cotyledons fall off early (Compton 1912).

Bark is brown to black, rough and longitudinally fissured. The stems are whitish and pubescent, becoming darker with age. They are woody and branch almost from the base of the plant. Branchlets glabrous to puberulous. Leaves (Figure 1) are glabrous to sub-tomentose, finely bipinnate with 3–10 branchlets to about 4 cm long, each with 10–25 pairs of narrow, oblong leaflets to about 6 mm long and 1.5 mm wide. There is a petiolar gland between the two pairs of branchlets closest to the stem. A pair of slightly deflexed, spinescent stipules, up to 50 mm long, occurs at the base of each leaf on younger stems (Figure 1) but these may be absent on more mature ones. The flowers (Figure 1) are small (corolla 2.5–3.5 mm long) bright yellow, typically wattle-like, in fluffy, spherical heads and about 12 mm in diameter, usually in clusters of 2 to 6, on a pubescent stalk with a few small bracts near the middle. The outline of the inflorescence consists of exserted stamens. Flowers do not produce nectar but have a pleasant odour like ripe melon. A number of stalked flower heads usually arise from each leaf joint (Figure 1). The fruit is an indehiscent pod, which is laterally flattened, grey-green darkening to green or brown when mature, tomentellous and deeply and irregularly constricted between each seed. The pod is from 6 to 25 cm long, 1 to 1.5 cm wide, is slightly sticky inside and contains 8 to 15 depressed, subglobular seeds. The length of the pod is correlated with the number of seeds it contains. The position of each seed is marked by a distinct raised bump in the valves. Seeds are subcircular, areolate and around 7 × 6.5 mm in size. Seeds have a very hard brown seed coat. Plants have a deep, woody taproot, with several branching, surface, lateral roots.

The nine subspecies form a polyploid complex with most being tetraploids but for ssp. *indica* the chromosome number is $2n=8x=104$ (Nongonierma 1976).

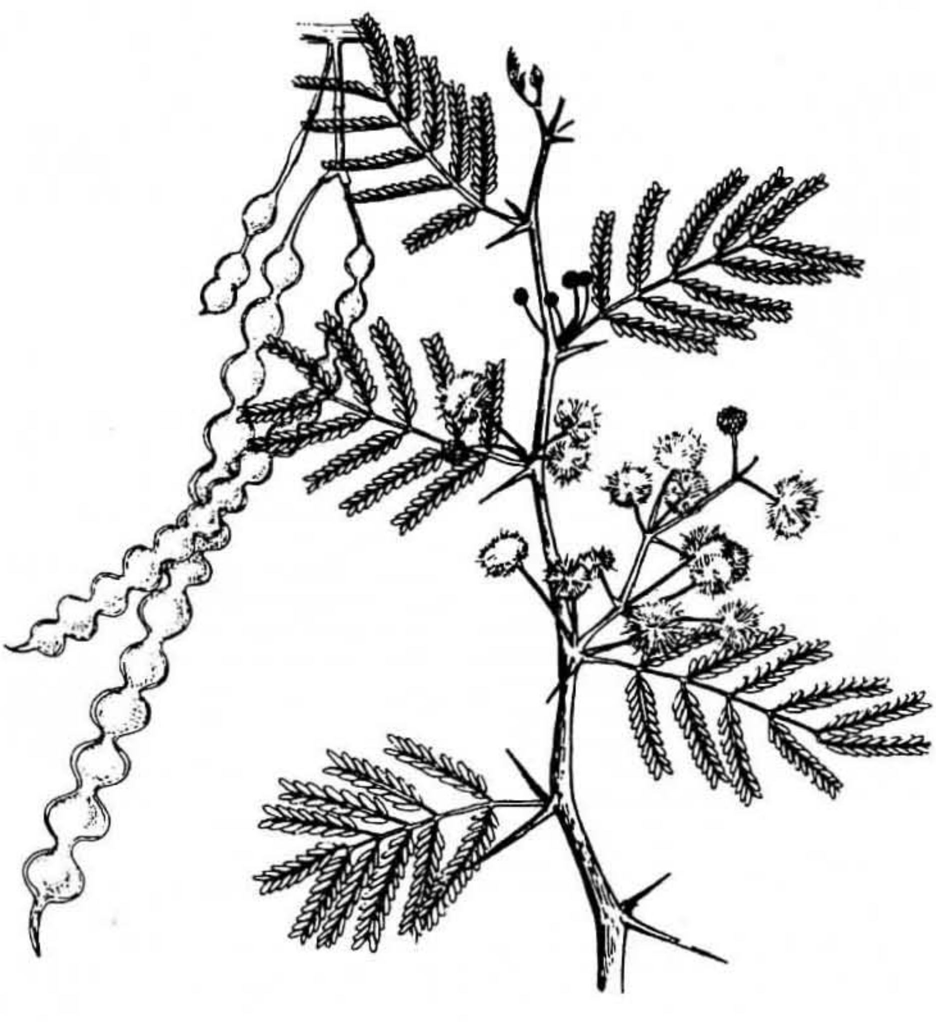

**Figure 1.** ***Acacia nilotica*** **ssp.** ***indica*****: leaves, flowers and pods.**

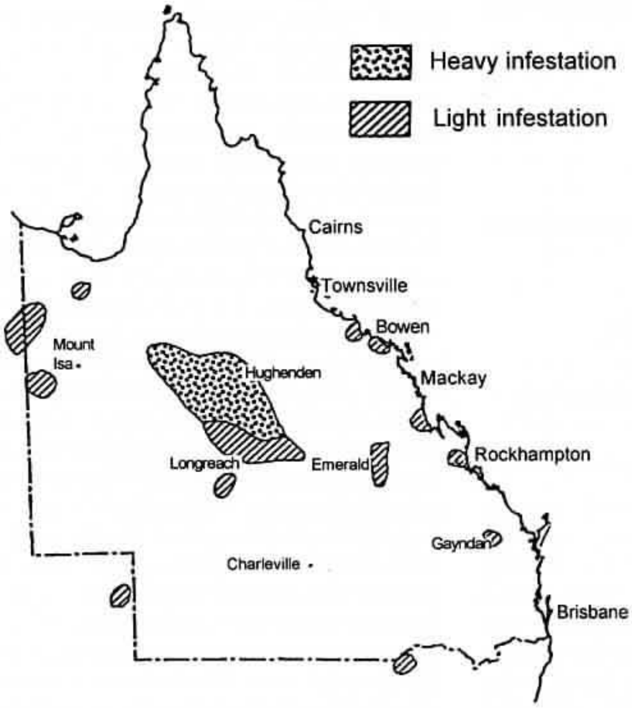


**Figure 2. The distribution of prickly acacia in Australia based on Carter (1989a).**

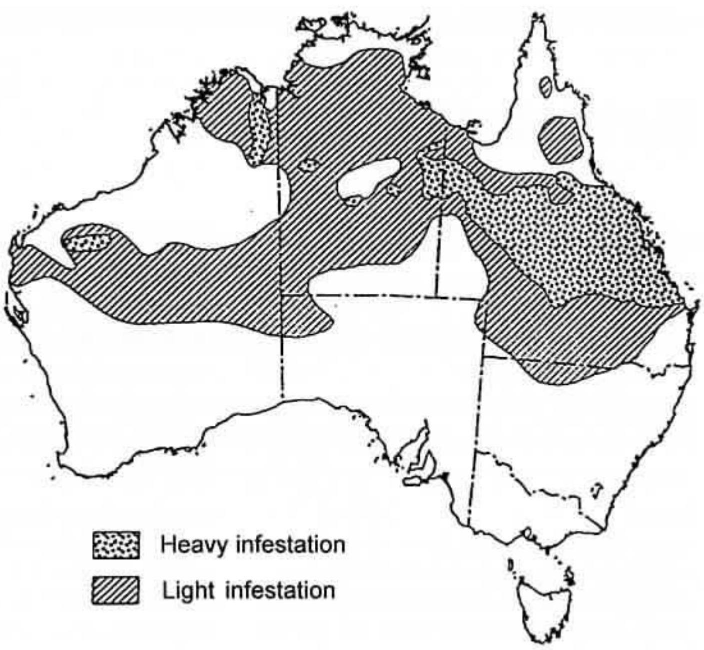


**Figure 3. The predicted potential distribution of prickly acacia in Australia based on Carter (1989a).**

*Distinguishing characters*

In Australia, prickly acacia is most likely to be confused with other prickly woody weeds in the Leguminosae: the mesquites (*Prosopis* spp.), parkinsonia (*Parkinsonia aculeata* L.) and mimosa bush (*Acacia farnesiana* (L.) Willd.). Prickly acacia is distinguished from mesquite and parkinsonia by its capitate flowers as opposed to the elongated flower spikes of mesquite and the pea-like flowers of parkinsonia. The leaves of prickly acacia are quite distinct from the long, flattened leaf with many small oblong secondary leaflets possessed by parkinsonia. Mesquite has one or two pairs of opposite segments, prickly acacia has three to ten pairs. Prickly acacia is best distinguished from mimosa bush by the pods which are constricted in prickly acacia but not constricted, cigar shaped and slightly curved in mimosa bush.

*Intraspecific variation*

*Acacia nilotica* is generally considered to be a single, but exceedingly variable, species. There are nine morphologically and ecologically distinct subspecies (Brenan 1983). The habit of the tree, shape of the crown, degree of pubescence of young branchlets and pods and the shape and size of the pods all vary significantly. In Kenya the zone of overlap between the subspecies is narrow and so the subspecies are easily distinguished, whereas in Pakistan, *A. nilotica* varies considerably in morphology, over a wide area. *A. nilotica* ssp. *indica* hybridizes with *A. nilotica* ssp. *hemispherica* and *A. nilotica* ssp. *cupressiformis* to produce widely distributed hybrid swarms (Ali and Faruqi 1969, Ali and Qaiser 1992). This hybridization has been confirmed by the study of the phenolic constituents of the leaves (Ali and Qaiser 1980, 1992). It is believed that the prickly acacia in north Queensland is *A. nilotica* ssp. *indica* and comes originally from India. However, variations in pod form, hearsay reports of introductions from Africa and at least one reported casé of possible hybrid sterility, suggest that introductions may have been made from other parts of prickly acacia's range. The assumption that all prickly acacia in north Queensland is subspecies *indica* is probably correct, but in view of the importance of correct identification, this assumption needs to be verified.

## History

Prickly acacia was first introduced into Queensland in the 1890s (Bolton 1989) from Pakistan and India. It was regarded as being *A. arabica* until 1940 (Hill 1940). There are reports of prickly acacia seeds being imported from southern and eastern Africa and established on Western Queensland properties (Bolton and James 1985). The first recorded specimens from Queensland were reported from Barcaldine in 1919. By the early 1920s it was grown extensively as a shade and ornamental tree in the Bowen and Rockhampton districts (Pollock 1926). In 1926 it was recommended by the Department of Agriculture and Stock as a suitable shade tree for sheep in western Queensland and was extensively planted around homesteads, bore drains and dams during the second quarter of this century, not only for shade but also for fodder because of the protein rich pods. Seeds were often carried around in saddle bags and distributed from horseback. By the 1930s prickly acacia was well established across the Mitchell grasslands of western Queensland and several coastal localities (Thompson 1992).

The wool crash of the 1970s caused an increase in cattle stocking rates. This, and the series of wet years during the 1950s and again in the 1970s promoted massive spread of prickly acacia throughout the northern downs and the establishment of dense impenetrable thickets. The slump in cattle prices during the 1970s led to high stocking rates which may also have been significant in providing large numbers of cattle as dispersal agents. Prickly acacia has been declared noxious under the Rural Land Protection Act since 9 March 1957.

## Distribution

*Outside Australia*

*A. nilotica* has a wide distribution, through the drier areas of Africa, from Senegal to Egypt, southwards to South Africa and eastwards to India (Ross 1979, Brenan 1983). The fact that populations in Africa and India cannot be distinguished at the specific level suggests that their separation is geologically recent and that populations were probably continuous through Africa and India when the two areas were connected by tropical forest and savanna (20–60 million years ago) (Ross 1981). *A. nilotica* ssp. *indica* is also widespread. It occurs in the P.D.R. Yemen, The Yemen Arab Republic, Oman, Pakistan (Punjab and Sind regions), India (Punjab, Uttar Pradesh, Bengal, Madhya Pradesh, Madras and Bombay regions) and Burma. Ross (1979) suggests the subspecies is native to India

**Table 1. Areas infested with prickly acacia in nine western Queensland Shires based on density estimates from individual properties (Densities: low – present on <5%; medium – present on 5–50%; high – present on >50% of the surveyed property) (Carter 1989a).**

| Shire | Low density | Medium density | High density | Total area (ha) | % Shire infested |
|---|---|---|---|---|---|
| Longreach | 17 739 | – | 6 652 | 24 391 | 1.0 |
| Aramac | 707 348 | 114 195 | 42 130 | 863 674 | 37.2 |
| Ilfracombe | 23 282 | – | – | 23 282 | 3.5 |
| Winton | 1 510 044 | 293 804 | 87 717 | 1 882 566 | 35.0 |
| Barcaldine | 7 760 | 19 956 | 2 217 | 29 934 | 3.6 |
| Flinders | 1 124 218 | 165 195 | 109 761 | 1 399 175 | 33.6 |
| Richmond | 833 739 | 339 261 | 180 717 | 1 353 718 | 50.3 |
| Cloncurry | 57 652 | – | – | 57 652 | 1.2 |
| McKinlay | 650 804 | 298 239 | 67 630 | 1 016 674 | 25.0 |
| Total | 4 932 591 | 1 230 653 | 487 826 | 6 651 071 | 28.4 |

but planted in Africa whilst Brenan (1983) notes that its habitats in Ethiopia and Somalia appear to be natural. It has been cultivated in Iran and Vietnam (Brenan 1983).

*Australia*
There are scattered populations across most of Queensland and isolated occurrences in the Northern Territory, New South Wales and South Australia. In Queensland, prickly acacia is currently distributed from Karumba in the north to the New South Wales border in the south, and from Bowen in the east, to the Northern Territory border in the west (Figure 2). The major part of the distribution includes 6.6 M ha of the northern Mitchell grass downs of Queensland. The heaviest infestation is along water courses and drainage lines. The total area covered by the infestation is not known but the results of mail surveys (Bolton and James 1985, Carter *et al.* 1991) (Table 1) indicate that in the nine shires surveyed, 6.65 M ha or 28% of the area, was infested. It is likely that in the 10 years since the survey was conducted, prickly acacia has expanded to cover well over 7 M ha.

## Habitat

Prickly acacia prefers arid to semi-arid warm-temperate to subtropical regions where it is found in woody grasslands and savannas (Parsons and Cuthbertson 1992). Adjers and Hadi (1993) state prickly acacia will tolerate extreme temperatures of -1 to 50°C. Whether frost limits prickly acacia distribution is not clear. Young plants are frost tender (Fagg 1992, Adjers and Hadi 1993) and frost is said to limit distribution by killing tops of plants and preventing seed set but there are reports that frost susceptible areas in Queensland, such as Gayndah, have populations of prickly acacia which are slowly spreading and setting seeds (Carter *et al.* 1991). Prickly acacia requires 250–1500 mm of rain per annum (Fagg 1992). It tolerates salinity well (Carter 1994) and if sufficient water is present will grow well in saline soils (Adjers and Hadi 1993). In Australia, prickly acacia prefers heavy cracking clay soils, heavy coastal clays and basalt soils. It establishes on lighter soils, usually as individual plants along cattle transportation routes (Bolton 1989).

The predicted distribution of prickly acacia in Australia (Carter 1989a, Carter *et al.* 1991) based on a BIOCLIM analysis using climatic information from part of the plant's range in India (Table 2) indicates that the majority of Queensland, the Northern Territory and much of Western Australia may be climatically suited to this species (Figure 3). The data used for the climatic matching do not represent the full extent of prickly acacia's climatic range and therefore the distribution shown in Figure 3 may be a conservative prediction. Conversely, other ecological factors such as soil types, probably limit its habitat range to part of that predicted from climate.

It would seem that climatically, prickly acacia is sufficiently well adapted to semi-arid, arid and northern Australia that it has the potential for a major increase in its area of infestation, and for increasing its population density in the region where it is already established.

## Growth and development

*Morphology*
Growth of prickly acacia occurs only if plants have access to a permanent water source or if volumetric soil moisture is >180 mm (Carter and Cowan 1993). Along bore drains where water is plentiful, trees are compact in habit, grow 4–5 m tall and are found in dense stands. Densities of up to 932 trees $ha^{-1}$ have been recorded (Thompson 1992). At such densities prickly acacia may produce an impenetrable spiny thicket, where seedlings are unlikely to establish. On open Mitchell grass downs trees tend to be more open, shorter and populations are more scattered. Seedlings are spiny but mature unbrowsed plants may not produce spines. Growth form can be modified by sheep browsing on the lower branches and removing stems to 5 mm diameter to give the appearance of a tree with a flattened or rounded spreading crown and a marked browse line. Well watered trees show an average annual increase in basal area of 22% whereas trees growing on the open downs, where there is no permanent water supply, only increased in basal area by 3.8% (Carter and Cowan 1993). On the open downs, significant tree growth is largely restricted to wet years. Lowry *et al.* (1993) reported that leaf yield and stem yield is not related to whole tree parameters although leaf yield is related to stem yield. There is only a poor relationship between leaf yield and branch length, weight and diameter.

*Phenology*
Leaf production and loss is determined by available soil water with broadly similar patterns occurring for trees on open downs country and bore drains. On open downs there is a positive correlation between leaf production and soil moisture (Carter *et al.* 1991), leaf production is low and in the dry season defoliation is severe. Seventy five per cent of leaves can fall before the end of the dry season (September) but refoliation is rapid and begins within days of rainfall. Trees with permanent water may become defoliated due to water stress as the low hydraulic conductivity of clay soils and the regular delving

**Table 2. Climatic variables used to predict the potential distribution of prickly acacia in Australia (Carter 1989a).**

| | Bio-climate: India Regions | | | Bio-climate: Australia Percentile values | | |
|---|---|---|---|---|---|---|
| | Bellary | Kalhiawer | Rajasthan | 5% | 50% | 95% |
| Mean annual temperature (°C) | 25.0 | 26.0 | 25.7 | 20.5 | 23.6 | 25.9 |
| Mean temperature range (°C) | 27.0 | 28.0 | 25.9 | 18.0 | 28.0 | 30.3 |
| Mean temperature of coldest month (°C) | 8.4–11.0 | 12.1–12.8 | 7.2–12.4 | 6.0 | 8.8 | 13.4 |
| Mean annual rainfall (mm) | 510–850 | 560–750 | 350–500 | 369 | 504 | 1222 |

of drains lowers water uptake (Carter and Cowan 1988). Prickly acacia has a large tap root and the lowering of the water table during dry conditions, with water uptake left to surface lateral roots, could also be an important factor in defoliation. Leaf production for trees both on and off bore drains shows marked seasonality. Production is lowest when pasture condition is also poor (October to November) (Lowry *et al.* 1993) although there is some new leaf produced and some leaf fall every few months.

Bud set and flowering occurs between November and the end of July with most flowering occurring in March–June (Carter 1994). Water stressed trees on open downs tend to have a more prolonged budding and flowering period which probably serves to increase pod production (J.O. Carter personal communication) whereas the development of pods on well watered trees could inhibit further flowering (Carter *et al.* 1991). Carter *et al.* (1991) also report that in 1987, a year of low rainfall in the Julia Creek area, all trees aborted a significant percentage of buds, flowers and green pods, with many trees away from water not setting any seed. Although moisture is important for flowering and bud set, temperature may also have a role. Temperature has a major effect on flowering and fruiting in Sudan (Khan 1970) although no such effects were reported by Carter and Cowan (1988). Pod production begins at the driest time of year (July) but the majority of pods abort before they are 1 cm long; the remainder ripen and fall early in the wet season (November to February) (Carter 1994, Carter and Cowan 1988). If soil moisture is sufficient, a proportion of seeds set germinate in spring. Germination is enhanced by scarification: by age, fire or by passage through a digestive tract. If soil moisture is abundant and there is little shading by other plants, growth can be rapid, but on open downs where it is drier, a good grass cover may reduce growth. Trees can flower and set seed 2–3 years after germination (Parsons and Cuthbertson 1992). Prickly acacia is adapted to the rapid use of soil water and, through leaf fall, to minimizing moisture loss at times of high water stress (Carter and Cowan 1988).

### *Mycorrhiza*

*Acacia* species form symbioses with a variety of bacterial and fungal strains but there are few observations concerning prickly acacia and none for prickly acacia in Australia. *Acacia* species are nodulated by a diverse range of rhizobia including both *Rhizobium* and *Bradyrhizobium* species which often vary in their nitrogen fixing effectiveness (Dart 1994). In some soils appropriate bacterial strains may be absent or populations too small for nodulation to occur. Prickly acacia nodulates in Pakistan (Athar 1993) and in Africa is known to nodulate only with fast growing *Rhizobium* species. In Australia, where prickly acacia has been established for some years, there is a relative decrease in soil organic carbon between canopied and open areas, suggesting enhanced soil nitrogen around trees (J.O. Carter personal communication). This is a pattern similar to that found for mesquite, where soil nitrogen and organic carbon are both higher in concentration and availability under mesquite than in adjacent open areas (Tiedemann and Klemmedson 1973, 1986, Klemmedson and Tiedemann 1986).

*Acacia* species can form ecto- and endomycorrhizal associations (Dart 1994) but there are no specific observations on prickly acacia. These two associations play crucial roles in the nitrogen and phosphorus nutrition of *Acacia* species and so there is probably a significant interaction between the two (Dart 1994) for prickly acacia also.

## Reproduction

### *Floral biology and seed production*

No studies of floral biology have been carried out in Australia and little is known about the reproductive strategy of prickly acacia elsewhere. The following account of prickly acacia in Kenya is taken from Tybirk (1989).

Flowers in an inflorescence open synchronously during the night. The anthers open and shed pollen only between 07.30 and 12.00 h of the following day, which is also when the stigmas are receptive. The flowers slowly wither in the afternoon of the same day. This pattern is in contrast to the protogyny of the Australian native acacias.

On average there were 90 flowers per inflorescence each with 92 anthers which gave an average of 1.1 million pollen grains per inflorescence. Seventy one per cent of flowers were staminate and functionally male and 29% were hermaphrodite. The percentage of hermaphrodites per tree varied between 0 and 84% ($n$=6). Pollination was carried out by 10 species of solitary bees. Flowers were not visited by honey bees. Each inflorescence, on average, was visited by bees 26 times in the two hour period between 09.00 and 11.00 h and 75% of bee visits were made during these two hours. This period is the time of day when the temperature is in the preferred range for bees, so pollen shedding occurs when bee activity is maximal. Thirty six per cent of stigmas retained a polyad after an inflorescence had been visited by bees and were considered to have been pollinated. All flowers produce pollen but the tree invests only in a few hermaphroditic flowers which are at the top of the inflorescence, in the most suitable position for pollination. The high number of pollen producing flowers ensures good pollen flow through the population. Since each flower has an average of 16 ovules and each polyad 16 pollen grains, one polyad has the potential to fertilize all the ovules of a carpel to produce 16 seeds. However on average each pod held only 10.8 seeds, so fertilization efficiency was only 68%. Pod set was 9% or 0.1 pods per flower, or, since not all flowers are hermaphroditic, 0.3 pods per (hermaphroditic) flower. Each inflorescence produced an average of 1.3 pods; each tree an average of 832 pods. Total seed production per tree was 153–34 000.

Some comparative data on seed and pod production are available for Australia (Queensland) (Bolton *et al.* 1987, Carter *et al.* 1991, Carter and Cowan 1993). Along a bore drain, 710 trees produced 18.6 and 24 million seeds in consecutive years or an average of 30 000 seeds per tree. Each pod contained 9.22±0.78 seeds so each tree produced an average of 3253 pods. Whilst the number of seeds per pod (and therefore probably fertilization efficiency) in Queensland is not different from in Kenya, pod production is at the high end of the range for Kenya. Seed production is very high (and occurs every year) if trees are well watered (Carter and Cowan 1993) and since the trees studied in Queensland were on a bore drain this could explain the difference. On open downs where there is less water, a tree may produce only a few pods or none at all. Without late winter or early spring rain trees produce only 5–50 pods (Carter *et al.* 1991). Seed production can range from 1260 seeds $m^{-2}$ of canopy along a bore drain to 6 seeds $m^{-2}$ of canopy on a dry basalt ridge (Bolton *et al.* 1987).

### *Dispersal*

Dispersal of prickly acacia is solely due to the movement of seeds. In its native range it is dispersed by browsers such as gazelles, elephants and antelope (Carter *et al.* 1991) but Australia has no native browsers and domestic livestock are the main agent of dispersal. Cattle are generally regarded as favouring the spread of prickly acacia more than sheep. Cattle pass about 80% of the seeds they eat and approximately 40% of these are viable. The faeces provide an environment which enhances germination and survival (Harvey 1981). Sheep pass few viable seeds in their faeces, but spit out about 35% of seed during ingestion and regurgitate about a further 15% as viable seed (Carter and Cowan 1988). Since seed takes at least 6 days to pass through the gut, stock moved by road transport can cause viable seed to be dispersed over large distances. Further, floods from heavy rain disperse seeds down catchments (Carter 1994). Seed may also be dispersed in mud adhering to the legs of animals. Information on seed dispersal by

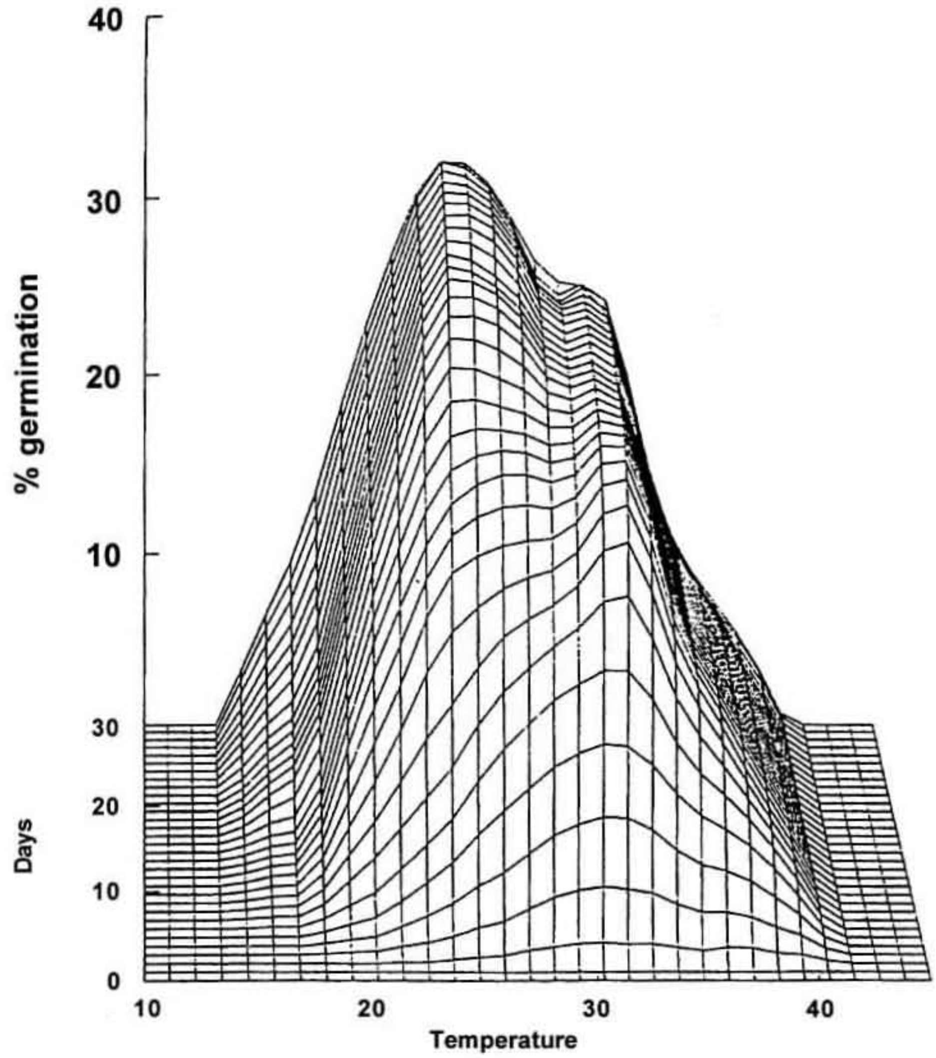


**Figure 4. The effect of temperature on the germination of prickly acacia seeds (from Carter *et al.* 1991).**

native animals is minimal. Carter (1994) suggests emus do not disperse prickly acacia, but this is disputed (P. Jeffrey personal communication). Strong winds can carry seed pods from tall trees over short (<25 m) distances (Carter and Cowan 1993).

*Physiology of seeds and germination*

Seed dormancy and longevity are vital factors contributing to the weed status of prickly acacia. As with all legume seed, the outer epidermis of prickly acacia seed is woody and forms a rigid mechanical layer (Corner 1951, 1976) which is impermeable to water. Dormancy therefore conforms to the Type 2 dormancy of Crocker (1916). Dormancy is exogenous (Palani *et al.* 1995) and germination does not occur until triggered by water penetrating the hard seed coat which has been abraded gradually in the soil or disrupted by an event such as fire. On bore drains seed half life is about 10 months (Carter *et al.* 1991) but seed can remain viable for seven years (Bolton *et al.* 1987) and the seed bank can contain from 5–724 intact seeds per square metre, so under favourable environmental conditions heavy reinfestation could occur in areas where established plants have been controlled for some years. About 73% of seeds are germinable after pod drop and about 26% are hard, dormant seeds (Bolton *et al.* 1987). The majority of seeds resides in the litter layer with <1% being in the soil (Bolton *et al.* 1987). Germination occurs between 14 and 37°C, with maximum germination occurring at 25°C (Figure 4). There are no significant differences between seeds germinated in a light regime of 12 h light/12 h dark and seeds maintained in the dark (Carter *et al.* 1991) but seedlings are shade intolerant (Fagg 1992). Germination of seeds from plants in mild coastal conditions was relatively rapid while seed set under moisture stress in western Queensland were slow to germinate and had a high percentage of hard (dormant) seeds. Six year old seed removed from cattle dung had a 22.5% germination rate, which may have been higher had all the seeds been scarified (Bolton *et al.* 1987). Carter *et al.* (1991) state that seed size was also influenced by aridity at the time of seed set.

Germination of cattle ingested seeds can start within three days if temperatures are not extreme with most 'soft' seeds germinating within 28 days. The number of viable seeds is reduced by passage through the gut of cattle, sheep and goats but surviving seeds have higher rates of germination (Bolton *et al.* 1987). Sheep and goats destroy more seed than cattle (Harvey 1981, Carter *et al.* 1991).

Brown and McIvor (1993) conducted a study on the effects of black speargrass (*Heteropogon contortus* (L.) Beauv. ex Roemer & Schultes) and Indian couch (*Bothriochloa pertusa* (L.) A. Camus), three defoliation rates of these grasses and three different watering regimes on the germination and establishment of prickly acacia. Seedling emergence and survival were monitored over 90 days and the survival rate exceeded 95%. The authors concluded that the competitive effects of the herbaceous layer were unlikely to limit prickly acacia invasion. However neither the soil type used nor the grass species are naturally associated with prickly acacia.

Brown and McIvor (1993) also introduced seeds into field plots dominated by perennial grasses that had been protected from grazing for over 20 years. Prickly acacia survival over two years was 62% even though seeds had been planted at the beginning of two very dry seasons.

Establishment of seedlings is episodic and whilst conditions which cause mass germination and establishment of prickly acacia have not been quantified, they seem associated with La Niña influences, which produce a series of above median summer rainfalls (Thompson 1992, Carter and Cowan 1993). Although seedling establishment can occur in drier times, survival is low. If rainfall following germination is below average, the majority of seedlings on black soil will die within two years (Carter and Cowan 1988). Thompson (1992) modelled mass establishment in the northern Mitchell grass downs on the basis that the grey-brown cracking clay soils of the region require an initial rainfall event of 75–100 mm for water to permeate through the top soil and that 25–75 mm of rain falls in consecutive months following the initial rainfall event, to allow seedlings to develop a sufficient root system to survive to the next wet. The model successfully represented the mass establishment of prickly acacia in the 1970s.

*Vegetative reproduction*

Prickly acacia does not reproduce vegetatively although it shows crown regrowth after fire damage and from cut, slashed or dozed stumps unless the roots are cut 15–30 cm below the soil surface.

## Hybrids

No interspecific hybrids have been recorded in Australia. Hybridization between subspecies is widespread in Pakistan (Ali and Faruqi 1969, Ali and Qaiser 1980).

**Figure 5. A flowering stem of prickly acacia with the previously treeless Mitchell grass downs in the background.**

**Figure 6. Prickly acacia stands become very dense along bore drains impeding stock access to water.**

### Population dynamics

The invasion of the Mitchell grass plains of northern Queensland by prickly acacia has followed a stepwise exponential pattern (Carter 1994) with some spread every few years but with most occurring in very wet years. Several biological characteristics have been responsible for this rapid invasion. Seed production can be very large where there is sufficient water and seeds can be very long lived. Once established, seedlings are protected from grazing by thorns and they are tolerant of fire (Pratt and Knight 1971, Carter *et al.* 1989) and soil salinity (Fagg 1992, Carter *et al.* 1991). In the Mitchell grass plains there are no other tree species with which prickly acacia has to compete. Prickly acacia appears well adapted for the rapid use of good soil moisture and can tolerate conditions of low soil moisture (Carter *et al.* 1991). Since the trees are relatively long lived (30–60 years) (Carter 1994) and can survive the erratic rainfall regime of north-western Queensland, they have the potential to respond to the infrequent occasions when good winter rains are followed by good summer rains and conditions for reproduction are excellent.

### Importance

*Detrimental*

**Grazing.** The major part of the distribution of prickly acacia includes 6.6 M ha of the grazing country of the northern Mitchell grass downs of Queensland (Figure 5). The heaviest infestation is along water courses and drainage lines. The total area covered by the infestation is not known but the results of a mail survey (Bolton and James 1985, Carter *et al.* 1991) (Table 1) indicates that in the nine shires surveyed, 6.65 million hectares or 28% of the area, and 1200 km bore drains were infested. Dense infestations of prickly acacia significantly reduce pasture production, increase mustering time and cost, exacerbate soil erosion, impede stock movements and the access of stock to water (Figure 6) and increase water loss from, and maintenance costs of, bore drains.

The main economic damage is due to the reduction in pasture production (Figure 7). Under normal grazing pressure a 25–30% canopy cover (2 $m^2$ $ha^{-1}$ basal area) of prickly acacia reduces pasture production by 50% compared with acacia-free pasture (Carter 1994), and pasture growth is virtually prevented by a 50% canopy cover (J.O. Carter personal communication). Maximum canopy cover in north-west Queensland is about 35% (3.5 $m^2$ $ha^{-1}$ basal area). The amount by which prickly acacia reduces the perennial grasses depends on moisture and nutrients (site potential) and as conditions become drier during drought, grass production is increasingly suppressed. Annual and ephemeral plant species appear not to be affected (Carter 1994). On one property Mitchell grass basal areas showed a decline from 2.4% at 0 trees $ha^{-1}$ to 0.01% at 932 trees $ha^{-1}$

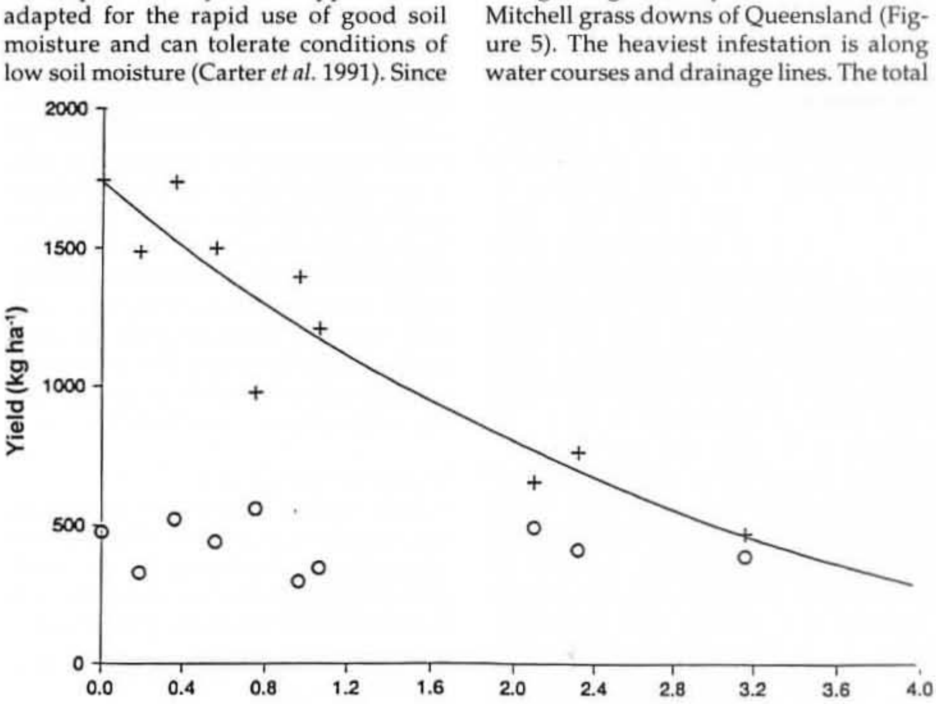


**Figure 7. The effect of prickly acacia on grass production (+ perennial grasses, O annual herbs; from Carter 1994).**

(Thompson 1992). The reduction in grass cover could be due to a number of factors, including water, nutrients, trampling, shade and an increased ability of stock to consume grass of low quality. The key factors are probably competition for moisture and increased grazing pressure.

The tree-grass relationship in savanna communities is thought to be driven by available water (Burrows *et al.* 1988). Woody plants can exploit subsoil moisture while grasses compete with woody plants for water in the topsoil. This topsoil water can be very variable. Mitchell grasses differ from other savanna grasses as they possess a dual surface and deeper taproot system, similar to woody plants, allowing them to survive episodic drought. Burrows *et al.* (1988) suggest that the ability of Mitchell grass to utilize water throughout the soil profile helps to explain why this vegetation type has remained essentially treeless, although nutritional factors, fire and grazing are also likely to be important. The above authors attribute the prickly acacia invasion into Mitchell grass plains to widespread planting of prickly acacia seeds, increasing numbers of cattle and sequences of favourable years for germination and establishment. Mitchell grass was not colonized by native invaders because of regular burning and native species not having the regenerative capacity and dispersal mechanisms as shown by prickly acacia (Burrows *et al.* 1988). Grass cover reduction occurs under prickly acacia as stock congregate around trees for shade, foliage and pods, increasing both trampling and grazing. This reduction in pasture growth translates directly into a reduction in carrying capacity of the affected pasture for stock. Many graziers report that prickly acacia infestation does not reduce carrying capacities and accordingly do not adjust stocking rates on infested land. This is partly due to the substitution of prickly acacia leaf for pasture, but it is only a few years before the Mitchell grass is lost due to the increased grazing pressure. Eventually, stocking rates will have to be reduced to prevent the complete degradation of Mitchell grass pastures (Carter and Cowan 1993).

Mustering costs in dense prickly acacia have been estimated at $A17 per head, more than 10 times the usual cost of $A1.50 per head (Thompson 1992). Clean mustering a heavily infested paddock is very difficult. Stock remaining in these paddocks after a poor muster are increasingly difficult to handle, and harbour diseases and parasites that can rapidly re-infect treated stock returning to the paddock. Mustering from heavily infested paddocks may not be possible without the added cost of pushing tracks through the prickly acacia. Mustering is also impeded by the very dense thickets that develop along bore drains and, moreover, restrict stock access to water and make maintenance of the bore drains difficult.

The overall impact of prickly acacia on animal production in the infested region can be judged from Table 1, although it must be remembered that the data were collected on a property unit basis. Another series of wet years would result in much of the 6 m ha with low or medium density developing to high density infestations, with virtually complete loss of animal production from a third of the Mitchell grass downs. The likely cost to the grazing industry in terms of reduced production would exceed $A5 million annually (agricultural production in the five shires most affected by prickly acacia averaged $A142 million in 1991–94) (ABS: Value of Agricultural Commodities Produced collection).

**Table 3. The estimated cost for a one-off control of prickly acacia in the nine western Queensland shires of Table 1.**

| | Area (million ha) | Cost $A ha$^{-1}$ | Total cost ($A million) |
|---|---|---|---|
| Low density | 5.0 | 1.5 | 7.5 |
| Medium density | 1.2 | 12.75 | 15.3 |
| High density | 0.5 | 45.00 | 22.5 |
| Sub-total | | | 45.3 |
| Follow-up | | | 10.1 |

**Table 4. Herbicides registered in Queensland for the control of prickly acacia.**

| Chemical | Application | Rate | Cost per specified rate ($A)[A] | Cost per tree[B] |
|---|---|---|---|---|
| Fluroxypyr | basal bark | 1 L per 100 L diesel | 26 + diesel | 12–16¢ |
| Triclopyr | basal bark | 0.83 L per 100 L diesel | 53.50 + diesel | 13–19¢ |
| Triclopyr/picloram | basal bark | 0.83 L per 100 L diesel | 41.50 + diesel | 11–13¢ |
| 2,4-D ester | basal bark | 1.25 L per 100 L diesel | 18 + diesel | 11–15¢ |
| Hexazinone | spot gun individual plants | 4 mL per m tree ht | | 4.2¢ per spot per m ht |
| Diuron | bore drains | 64 L ha$^{-1}$ | 470 | $A40 km$^{-1}$ drain |

[A] Prices are from Brisbane, January 1994.
[B] Jeffrey (1992).

**Control costs.** It is probable that at least 6.6 million hectares of grazing lands are infested with prickly acacia (Table 1) but due to the variable levels of infestation, any estimate of the total cost for controlling prickly acacia over this area must be uncertain and indicative only. The three infestation levels used in Table 1 are not formally defined, but information in Jeffrey (1992) suggests the three infestation categories could be defined as follows: light, 1–20 plants ha$^{-1}$; medium, 20–150 plants ha$^{-1}$; heavy more than 150 plants. Taking the median infestation rates for light and medium infestations, the average cost for chemical control as 15¢ per plant (Table 4) and mechanical control for heavy infestations at $A45 ha$^{-1}$ gives the costs listed in Table 3.

All control options require follow up treatments. If it is assumed that the cost of such treatment approximates the cost for treating a light infestation, then for the total area of infestation the cost would approximate an additional $A10 million, giving an estimate of about $A55 million to treat the current infestation. This is a conservative estimate as it does not include on-costs for the control programme. Of course further treatment would be needed in years subsequent to the main and follow-up treatment to ensure continuation of control.

In five western Queensland shires infested with prickly acacia, the mean property size is approximately 18 000 ha with 20 km bore drains (Bolton and James 1985). Assuming the average infestation levels of Table 1 on such a property and the previous definitions of the infestation levels, the cost of controlling prickly acacia on an average property, including a follow up treatment is $A46 450. This is likely to be beyond the resources of many graziers.

Currently, the Queensland Department of Natural Resources expends about $A40 000 annually on the control of prickly acacia on unallocated crown land. In 1992–93 the councils of the five most affected shires probably spent less than $A40 000 annually on prickly acacia. Undoubtedly the majority of costs are borne by landholders, many of whom use fencing, stock management, herbicides and mechanical measures for control of prickly acacia. P. Jeffrey (personal communication) estimates that $A3–4 million annually is currently spent by landholders on control.

**Land value.** A reduced value of leased land assets is potentially a major cost of prickly acacia infestations. Heavily infested land is almost worthless since reclamation costs are often close to, or exceed, the value of uninfested land. The flow on effects of land revaluation, such as reduced rents for infested leasehold properties, if

**Figure 8. Transformation of the Mitchell grass downs by prickly acacia to a thorny scrubland. Compare with Figure 5 and note the loss of grass.**

poorly managed, could become disincentives for the control of prickly acacia, which would lead to further reductions in land values.

**Natural ecosystems.** The environmental cost of prickly acacia is significant but difficult to quantify. The Mitchell grass downs (Figure 5) cover 21.9 million hectares in Queensland and lesser areas occur in the Northern Territory and Western Australia (Orr and Holmes 1984). They are one of the major grassland ecosystems of the world. Whilst the prickly acacia infestation is restricted to Queensland and a small area of the Barkly Tableland in the Northern Territory, there is no doubt that the Mitchell grass downs are being converted into a thorny scrubland similar to the African thornveld (Figure 8). Because it is changing such a large and important ecosystem, prickly acacia is considered one of Australia's worst environmental weeds. The impacts of this invasion on biodiversity and the ecology of native species have not been systematically studied. Since even a moderate canopy cover of prickly acacia reduces grass cover markedly (Figure 7) and changes the relative abundance of native plant species in favour of forbs and annual grasses, this, and the shift in structure toward a shrub community, is producing a dramatic effect on native fauna habitat and the overall ecology of the system.

**Hosts for other pests.** Prickly acacia is a host for a variety of organisms which attack it, but it does not appear to be a primary host for any other pests in Australia, although the Australian plague locust (*Chortoicetes terminifera* (Walker)) is reported to feed on it (Ablin 1989).

*Beneficial*

Throughout its native range, prickly acacia is considered to be a particularly useful tree (Fagg 1992) and in the Sudan it is the most important timber tree (El Atta 1993). Its wood is strong and durable and has a high calorific value (4950 kcal $kg^{-1}$), making it an excellent fuelwood. It is grown throughout India, Pakistan and parts of Africa for timber and fuel (Bisht and Toky 1993, Garg 1993, Ginwal *et al.* 1995, Hooda *et al.* 1993, Lamers *et al.* 1994, Mathur *et al.* 1984, Menwyelet Atsedu *et al.* 1994, Palani *et al.* 1995, Srivastav 1994, Tandon *et al.* 1988, Tesfaye Abebe 1994). It is also used for rehabilitation of saline lands, as a source of tannins for tanning leathers and as a traditional medicine, molluscicide and algicide (New 1984, Fagg 1992, Nadagondar 1993). However, in Australia, because of its invasiveness and the difficulty and cost of effectively maintaining prickly acacia at acceptable levels, most landholders view the presence of prickly acacia in their paddocks as undesirable. Prickly acacia is suitable for pulping and paper production (Nasroun 1979) but a study into the feasibility of woodchipping current infestations indicated that harvesting was not economic (Thompson 1992).

On the Mitchell grass downs, shade from Athel pines (*Tamarix aphylla* (L.) Karsten) can increase lambing percentages by 16% (Roberts 1984) so it is likely that at low densities prickly acacia could produce similar increases in lambing. Prickly acacia could also enhance stock productivity through the provision of pods and leaves as fodder during dry periods of the year when there is an absence of green feed (Carter 1994). Carter (1989b), Carter *et al.* (1991) and Lowry *et al.* (1993) give details of the feed value and nutrient levels of prickly acacia. Its leaf is very digestible (67%, Carter and Cowan 1988) and has a high protein content (16–17%, Carter and Cowan 1988) and sufficiently high levels of micronutrients, except for sodium (Carter 1994). Although it has a high feed value, it is a poor browse on its own (Lowry *et al.* 1993). In the Mitchell grasslands, prickly acacia can therefore act mainly as a protein supplement although high levels of tannins (30%, Carter *et al.* 1991) in the plant may bind protein and suppress animal production.

### Legislation

Prickly acacia was declared a noxious weed in Queensland in 1957 and currently is classed as P3 (the plant must have its numbers reduced in the heavily infested areas of the state) in the heavily infested shires of the Mitchell grass downs and P2 (all plants should be completely destroyed) in the remainder of the state. In the Northern Territory it is a Class A (to be eradicated) and C (introduction into the Territory is prohibited) plant.

## Weed management

*Herbicides*

There are a variety of control options for prickly acacia, with the most important being chemical control for light and medium density infestations. Current chemical control methods use basal barking, cut stump application, stem injection and overall foliar spray. Soil applied herbicides are used in the treatment of bore drains.

The phenoxy acid and pyridine based auxin simulators, 2,4-D ester, fluroxypyr and triclopyr are the most widely used and effective herbicides employed, both in basal bark spraying and cut stump application (Table 4). Basal bark spraying is best carried out when plants are actively growing (Carter and Cowan 1988) during early summer rains through to April (Carter *et al.* 1989). Used in this way, mortalities of >90% can be achieved (Jeffrey and Dodd 1992) and it is the most effective way of treating light and medium infestations. Cut stump application can be carried out throughout the year, requires less herbicide than basal bark spraying and achieves similar results. Fluroxypyr is also used as an overall foliar spray and is most effective when the plant is growing and is <1.5 m tall (Jeffrey and Dodd 1992).

The photosynthesis inhibiting herbicides diuron, hexazinone and tebuthiuron have been used with varying success in the control of prickly acacia. Diuron is successfully used to control heavy prickly acacia infestations along side bore drains and turkey nest dams but the results from using hexazinone and tebuthiuron have been variable (Jeffrey and Dodd 1992). Ground application of hexazinone and tebuthiuron rely on uptake by the plant through the roots and in regions with light soils and higher rainfalls is generally successful. Across much of the distribution of prickly acacia on the Mitchell grass downs, soils are heavy, rainfall is usually low and prickly acacia is deeply rooted so application to the soil surface is not viable. Nevertheless, the application of hexazinone to the base of the plant with a spot gun, or to the root zone by ground insertion lance overcomes these problems to give good reliable results everywhere, and is the best herbicide option for scattered plants in open downs (Jeffrey and Dodd 1992).

Dense infestations along creek lines remain difficult to treat with herbicide. The aerial application of fluroxypyr is a promising control option and in trials a 62–90% mortality of plants has been achieved. Mortality is reduced if stands are very dense and the trees large, but mortality may be such that a limited ground application of herbicide is all that is required as a follow up treatment (Jeffrey 1994).

Herbicides currently registered for control of prickly acacia and estimated costs for their use are summarized in Table 4.

*Other treatments*

It has been suggested that livestock grazing pressure (and therefore reduced competition from grasses and herbs) and the disruption of the fire regime, has allowed the invasion of woody weeds into the rangelands of northern Australia (Brown and McIvor 1993). In the Mitchell grass plains where much of the prickly acacia infestation occurs, fire is not used as a management tool and it is thought this may have favoured the invasion by prickly acacia (P.L. Jeffrey personal communication). The effects of fire and competition on the establishment of prickly acacia seedlings has not been extensively investigated but on limited evidence Brown and McIvor (1993) conclude that competition is unimportant and that the herbaceous layer is more important in providing fuel for fires. However, prickly acacia does not seem susceptible to fire (Pratt and Knight 1971, Carter *et al.* 1989) and germination may be stimulated (P.L. Jeffrey personal communication, Parsons and Cuthbertson 1992).

Mechanical clearance by dozing or double chain pulling (Jeffrey and Bode 1992) can be effective but is only applicable to heavy infestations as an aid to property management, since soil disturbance creates a well prepared seed bed for reinfestation (Thompson 1992, Jeffrey and Bode 1992). The use of a low energy mechanical grubber to cut the roots of individual trees below the soil surface largely overcomes this problem (Thompson 1992) and is comparable in costs to the use of herbicides (Table 4). Follow up treatment is required to control small plants, regrowth and the massive seedling emergence which can follow mechanical treatments.

There is some evidence (Carter 1994, Carter *et al.* 1990, Cobon and Reynolds 1991) that heavy grazing by sheep and goats can help control small prickly acacia seedlings and reduce tree growth. Grazing cattle and goats may help reduce canopy cover since cattle can browse to a greater height than sheep and goats.

Since prickly acacia is predominantly dispersed by stock, property hygiene is one way in which invasion of new areas and reinfestation of cleared ones may be controlled. Stock coming from infested areas during pod drop can be confined in a holding area for sufficient time for the gut to be completely cleared of seeds. Any seedlings that establish are localized and can be destroyed easily (Jeffrey 1989). If stock are grazed only in areas clear of prickly acacia during pod drop, the risk of seed dispersal across the property will be further avoided.

*Natural enemies*

A wide variety of generalized, native, leaf-feeding, sap-sucking, root, pod and seed feeding insects attack prickly acacia and stressed trees are attacked by bark and wood feeding insects (Ablin 1989). The native plant parasites *Lysiana subfalcata* (Hook.) Barlow and *Santalum spicatum* (R.Br.) A. DC. also attack prickly acacia (Carter 1989c) but neither have more than a very minor impact on the growth and spread of this weed (Carter *et al.* 1991).

Eight species of host specific and potentially damaging insect species from Pakistan (Table 5) (Mohyuddin 1986) have been identified as potential biological control agents. Only two species, *Bruchidius sahlbergii* Schilsky and *Cuphodes profluens* Meyrick, have been host tested (Marohasy 1995) and approved for field release. However, fewer than 4000 individuals of *C. profluens* were field released before the mass rearing programme was terminated and it is unlikely that this provided a large enough population for permanent establishment of the species. *C. profluens* was reported to have established at only one site (St. Lawrence, near Rockhampton). The trees here were subsequently destroyed in an unsuccessful attempt to eradicate prickly acacia in this region. In contrast, over 110 000 adults of *B. sahlbergi* were released. The insect is now well established and destroys up to 80% of new seed but it appears to be having a minimal

**Table 5. Insects from Kenya and Pakistan with potential as biological control agents for prickly acacia.**

| Species | Mode of action | Comment |
|---|---|---|
| **From Pakistan** | | |
| *Bruchidius sahlbergi* | mature seed feeding beetle | >110 000 released, established |
| *Cuphodes profluens* | green shoot boring moth | <4000 released, not established |
| *Anarsia trianota* | green shoot boring moth | not sufficiently host specific |
| *Ascalenia callynella* | green shoot boring moth | preliminary tests suggest host specific but difficult to rear in cages |
| *Cydia* sp. | stem galling moth | field surveys suggest is host specific but not tested |
| *Tephrina disputaria* | leaf feeding moth | small cage host tests ambiguous; needs retesting |
| *Bruchidius* sp. | mature seed feeding beetle | not tested |
| *Comibaena cassidera* | leaf feeding moth | not tested |
| *Chlorissa punctifimbria* | leaf feeding moth | not tested |
| **From Kenya** | | |
| *Weiseana barkeri* | leaf feeding beetle | release approved; mass rearing problems – egg dormancy |
| *Semiothisa inconspicua* | leaf feeding moth | preliminary tests indicate host specific |
| *Acizzia* sp. | sap sucking psyllid | host specific quarantine colony died out |
| *Acacidiplosis imbricata* | galls flower buds | field survey indicates host specific |
| *Acacidiplosis spinosa* | galls flowers | field survey indicates host specific |
| *Aposchizomyia acuta* | galls stem ends | field survey indicates host specific |
| *Bruchidius grandemaculatus* | mature seed feeding beetle | preliminary tests suggest specific to s.g. *Acacia* |
| *Risbecoma capensis* | green seed feeding insect | field surveys suggest specific to s.g. *Acacia* |
| *Tephrina* sp. | leaf feeding moth | field surveys suggest specific to s.g. *Acacia* |
| *Aspidoproctus* sp. | sap sucking scale insect | field surveys suggest specific to s.g. *Acacia* |

impact on the spread of prickly acacia (Carter and Cowan 1988). A large percentage of seed is eaten by stock and remains viable in cow dung, where it is inaccessible to these insects as they will only search for seed in pods under or on trees.

Nine insect species from Kenya (Marohasy 1995) (Table 5) are potential biological control agents. Only one species, *Weiseana barkeri* Jacoby, has been completely tested for host specificity and in September 1994, permission was given for its field release. However, rearing problems remain. Those associated with the provision of a suitable oviposition structure have been overcome (Marohasy 1994) but a reliable method for breaking egg diapause remains elusive.

Over 260 species of insect have been recorded as feeding on prickly acacia in its native range but even so this list is incomplete (Marohasy 1995). Whilst the suitability of most of these species as biological control agents is unknown (Marohasy 1993) the potential for finding suitable species from such a large pool must be high. Marohasy (1993) suggests that gall midges may be particularly suitable. Despite the releases so far carried out, the biological control of prickly acacia must be considered to be in its early stages.

In its native range, prickly acacia is also attacked by pathogens. These are best known from India and Pakistan, where *Septogloeum acaciae* H. Syd. produces leaf spots, *Septoria mortolensis* Penz. & Sacc. leaf blight, *Ravenelia acaciae-arabicae* P. Henn. rust, *Hypoxylon acaciae* P. Henn. canker, *Phellinus badius* (Berk.) Cooke, *Phellinus rimosus* (Berk.) Pilat (=*Phellinus pappianus* (Bres.) Ryvarden) and *Ganoderma lucidum* (Curtis:Fr.) P.Karst root rot and *Ganoderma applanatum* (Pers.) Pat., *P. badius, F. fastuosus* (Léveillé) Ahmad and *P. rimosus* heart rot (Lee Su See 1993).

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### References

Ablin, M. (1989). Biological control of prickly acacia. Richmond prickly acacia field day, 19 September 1989. Unpublished report, Queensland Department of Lands, Brisbane.

Adjers, G. and Hadi, T.S. (1993). Acacias in agroforestry. *In* 'Acacias for rural, industrial and environmental development', eds. K. Awang and D.A. Taylor, pp. 134-7. (WIIAP and FAO, Bangkok, Thailand).

Ali, S.I. and Faruqi, S.A. (1969). A taxonomic study of *Acacia nilotica* complex in W. Pakistan. *Pakistan Journal of Botany* 1, 1-8.

Ali, S.I. and Qaiser, M. (1980). Hybridization in *Acacia nilotica* (Mimosoideae) complex. *Botanical Journal of the Linnaean Society* 80, 69-77.

Ali, S.I. and Qaiser, M. (1992). Hybridization between *Acacia nilotica* ssp. *nilotica* and *Acacia nilotica* ssp. *cupressiformis*. *Pakistan Journal of Botany* 24, 88-94.

Athar, M. (1993). Nodulation status of some legume trees of Pakistan. *Nitrogen Fixing Tree Research Reports* 11, 32-4.

Bisht, R.P. and Toky, O.P. (1993). Growth pattern and architectural analysis of nine important multipurpose trees in an arid region of India. *Canadian Journal of Forest Research* 23, 722-30.

Bolton, M.P. (1989). Biology and ecology of prickly acacia. Richmond prickly acacia field day, 19 September 1989. Unpublished report, Queensland Department of Lands, Brisbane.

Bolton, M.P., Carter, J.O. and Dorney, W.J. (1987). Seed production in *Acacia nilotica* subsp. *indica* (Benth.) Brenan. Proceedings of the Weed Seed Biology Workshop, Orange, New South Wales, pp. 29-34.

Bolton, M.P. and James, P.A. (1985). A survey of prickly acacia (*Acacia nilotica*) in five western Queensland shires. Stock Routes and Rural Lands Protection Board, Brisbane. Internal report, November 1985, Queensland Department of Lands, Brisbane.

Brenan, J.P.M. (1983). 'Manual on taxonomy of *Acacia* species: Present taxonomy of four species of *Acacia* (*A. albida, A. senegal, A. nilotica, A. tortilis*)', pp. 20-4. (FAO, Rome.)

Brown, J.R. and McIvor, J.G. (1993). Ecology of woody weed invasions in the tropical woodlands of north-eastern Australia: implications for management. Proceedings 10th Australian and 14th Asian-Pacific Weed Science Conference, Brisbane, Volume 1, pp. 471-4.

Burrows, W.H., Scanlan, J.C. and Anderson, E.R. (1988). Plant ecological relations in open forests, woodland and shrublands. *In* 'Native pastures in Queensland. The resources and their management', eds. W.H. Burrows, J.C. Scanlan and M.T. Rutherford. (Queensland Department of Primary Industries Informations Series QI87023, Brisbane).

Carter, J.O. (1989a). Potential distribution of prickly acacia. Richmond prickly acacia field day, 19 September 1989. Unpublished report, Queensland Department of Lands, Brisbane.

Carter, J.O. (1989b). Food value of prickly acacia. Richmond prickly acacia field day, 19 September 1989. Unpublished report, Queensland Department of Lands, Brisbane.

Carter, J.O. (1989c). Plant parasites of prickly acacia. Richmond prickly acacia field day, 19 September 1989. Unpublished report, Queensland Department of Lands, Brisbane.

Carter, J. O. (1994). *Acacia nilotica*: a tree legume out of control. *In* 'Forage tree legumes in tropical agriculture', eds. R.C. Gutteridge and H.M. Shelton, pp. 338-51. (CAB International, Wallingford, UK).

Carter, J.O., Bolton, M.P. and Cowan, D.C. (1989). Prickly acacia: save dollars by early control measures. *Queensland Agricultural Journal* 115, 121-6.

Carter, J.O. and Cowan, D.C. (1988). Phenology of *Acacia nilotica* subsp. *indica* (Benth.) Brenan. Proceedings of the 5th Biennial Conference, Australian Rangeland Society, Longreach, Queensland, pp. 9-12.

Carter, J.O. and Cowan, D.C. (1993). Population dynamics of prickly acacia, *Acacia nilotica* subsp. *indica* (Mimosaceae). *In* 'Pests in pastures: Weed, invertebrate and disease pests of Australian sheep pastures', ed. E.S. Delfosse, pp. 128-32. (CSIRO, Melbourne).

Carter, J.O., Jones, P. and Cowan, D.C. (1991). Control of woody weeds in western Queensland (WRDF DAQ 25P). Report to the Australian Wool Corporation, Queensland Department of Primary Industries, Brisbane.

Carter, J.O., Newman, P., Tindale, P., Cowan, D. and Hodge, P.B. (1990). Complementary grazing of sheep and goats on *Acacia nilotica*. *Proceedings of the Australian Rangeland Society* 6, 271-2.

Cobon, D.H. and Reynolds, J.A. (1991). Role of complementary grazing by sheep and goats in improving stability and productivity of rangeland. Unpublished report DAQ3, Queensland Department of Primary Industries, Brisbane.

Compton, R.H. (1912). An investigation of the seedling structure in the Leguminosae. *Journal of the Linnaean Society* (*Botany*) 41, 1-122.

Corner, E.J.H. (1951). The leguminous seed. *Phytopathology* 1, 117-50.

Corner, E.J.H. (1976). 'The seeds of dicotyledons'. (Cambridge University Press, Cambridge).

Crocker, W. (1916). Mechanisms of dormancy in seeds. *American Journal of Botany* 3, 99-120.

Dart, P.J. (1994). Microbial symbionts of tree and shrub legumes. *In* 'Forage tree legumes in tropical agriculture', eds. R.C. Gutteridge and H.M. Shelton, pp. 143-57. (CAB International, Wallingford, UK).

de Vogel, E.F. (1980). 'Seedlings of dicotyledons'. (Centre for Agricultural

Publishing and Documentation, Wageningen).

El Atta, H.A. (1993). The effect of *Caryedon serratus* Olivier (Coleoptera, Bruchidae) on viability and germination of seeds of *Acacia nilotica* (L. Willd. ex Del.) in the Sudan. *Forest Ecology and Management* 57, 169-77.

Fagg, C.W. (1992). *Acacia nilotica* – pioneer for dry lands. NFT Highlights June 1992. NFTA 92-04.

Garg, V.K. (1993). Diagnostic leaf analysis for some fuelwood trees. *Indian Forester* 119, 17-24.

Ginwal, H.S., Rawat, P.S., Mohit Gera, Neelu Gera and Srivastava, R.L. (1995). Study of the pattern of seed germination of various subspecies cum provenances of *Acacia nilotica* Willd ex. Del. under nursery conditions. *Indian Forester* 121, 29-38.

Harvey, G.J. (1981). Recovery and viability of prickly acacia (*Acacia nilotica*) seed ingested by sheep and cattle. Proceedings 6th Australian Weeds Conference, Gold Coast, Volume 1, pp. 197-201.

Hill, A.F. (1940). *Acacia nilotica* (L.) Delile. Botanical Museum Leaflets of Harvard University No. 8, pp. 94-100.

Hooda, M.S., Raj Bahadur and Bangarwa, K.S. (1993). Growth and biomass yield of six multipurpose trees of arid and semi-arid India. *Nitrogen Fixing Tree Research Reports* 11, 8-9.

Jeffrey, P.L. (1989). Chemical control of prickly acacia. Richmond prickly acacia field day, 19 September 1989. Unpublished report, Queensland Department of Lands, Brisbane.

Jeffrey, P.L. (1992). Prickly acacia: current control methods and suggested strategies. Unpublished report, Queensland Department of Lands, Brisbane.

Jeffrey, P.L. (1994). Aerial trials on prickly acacia. Prickly acacia management – what works. Zara Station Field Day. 6 September 1994. Unpublished report, Queensland Department of Lands, Brisbane.

Jeffrey, P.L. and Bode, R. (1992). Chain pulling of prickly acacia. *Proceedings of the Weed Society of Queensland* 2, 36-40.

Jeffrey, P.L. and Dodd, A.P. (1992). Current control methods and suggested strategies. Unpublished report, Queensland Department of Lands, Brisbane.

Khan, M.A.N. (1970). Phenology of *Acacia nilotica* and *Eucalyptus microtheca* at Wad Medani (Sudan). *The Indian Forester* 96, 226-48.

Kleinschmidt, H.E. and Johnson, R.W. (1979). 'Weeds of Queensland'. (Queensland Department of Primary Industries, Brisbane).

Klemmedson, J.O. and Tiedemann, A.R. (1986). Long-term effects of mesquite removal on soil characteristics: II. Nutrient availability. *Soil Science Society of America Journal* 50, 476-80.

Lamers, J.P.A., Michels, K. and Vandenbeldt, R.J. (1994). Trees and windbreaks in the Sahel: establishment, growth, nutritive and calorific values. *Agroforestry Systems* 26, 171-84.

Lee Su See (1993). Diseases of acacias. *In* 'Acacias for rural, industrial and environmental development', eds. K. Awang and D.A. Taylor, pp. 225-32 (WIIAP and FAO, Bangkok, Thailand).

Lowry, J.B., Schlink, T.C. and Carter, J. (1993). Nutritional value of *Acacia nilotica* subspecies *indica* for sheep in Mitchell grass pasture. Unpublished report CSIO8P to the Australian Wool Research and Development Corporation, Queensland Department of Primary Industries, Brisbane.

Marohasy, J. (1993). Constraints to the introduction of biological control agents for prickly acacia. Proceedings 10th Australian and 14th Asian-Pacific Weed Conference, September 1993, ed. J. Swarbrick, Volume 2, pp. 33-8.

Marohasy, J. (1994). Biology and host specificity of *Weiseana barkeri* (Coleoptera: Chrysomelidae): a biological control agent for *Acacia nilotica* (Mimosaceae). *Entomophaga* 39, 335-340.

Marohasy, J. (1995). Prospects for the biological control of prickly acacia, *Acacia nilotica* (L.) Willd. ex Del. (Mimosaceae) in Australia. *Plant Protection Quarterly* 10, 24-31.

Mathur, R.S., Sharma, K.K. and Rawat, M.M.S. (1984). Germination behaviour of various provenances of *Acacia nilotica* ssp. *indica*. *Indian Forester* 110, 435-49.

Menwyelet Atsedu, Coppock, D.L. and Detling, J.K. (1994). Fruit production of *Acacia tortilis* and *A. nilotica* in semi-arid Ethiopia. *Agroforestry Systems* 27, 23-30.

Mohyuddin, A.I. (1986). Investigations on the natural enemies of *Acacia nilotica* in Pakistan. Unpublished report, PARC-CIBC Station, Commonwealth Institute of Biological Control, Rawalpindi.

Nadagondar, B.S. (1993). Acacias for rural, industrial and environmental development in India. *In* 'Acacias for rural, industrial and environmental development', eds. K. Awang and D.A. Taylor, (WIIAP and FAO, Bangkok, Thailand).

Nasroun, T.H. (1979). Pulp and paper making of some tropical hardwood species grown in the Sudan. *Sudan Silva* 4, 22-32.

New, T.R. (1984). 'A Biology of Acacias: A New Source Book and Bibliography for Biologists and Naturalists', pp. 153. (Oxford University Press, Melbourne).

Nongonierma, A. (1976). Contribution a l'etude du genre *Acacia* Miller en Afrique occidentale. II. Characteres des inflorescences et des fleurs. *Bulletin de l'IFAN Serie A* 38, 487-657.

Orr, D.M. and Holmes, W.E. (1984). Mitchell Grasslands. *In* 'Management of Australia's Rangelands', eds. G.N. Harrington, A.D. Wilson and M.D. Young, pp. 241-54 (CSIRO, Melbourne).

Palani, M, Dasthager, M.G. and Kumaran, K. (1995). Effect of presowing chemical treatment on germination and seedling growth in *Acacia nilotica*. *International Tree Crops Journal* 8, 189-92.

Parsons, W.T. and Cuthbertson, E.G. (1992). 'Noxious Weeds of Australia'. (Inkata Press, Melbourne).

Pollock, N.A.R. (1926). *Acacia arabica* as fodder. *Queensland Agricultural Journal* 52, 336-7.

Pratt, D.J. and Knight, J. (1971). Bush control studies in the drier areas of Kenya V. Effects of controlling burning and grazing management on *Tarchonanthus/Acacia* thicket. *Journal of Applied Ecology* 8, 217-37.

Roberts, G. (1984). Plotting a better future for lambs: A practical guide to producing shade. *Queensland Agricultural Journal* 110, 25-6.

Ross, J.H. (1979). A conspectus of the African *Acacia* species. *Memoirs of the Botanical Survey of South Africa* 44, 1-155.

Ross, J.H. (1981). An analysis of the African *Acacia* species: Their distribution, possible origins and relationships. *Bothalia* 13, 389-413.

Srivastav, A.K. (1994). Productivity and economics of some commercially important forest trees. *Indian Forester* 120, 12-29.

Tandon, V.N., Pande, M.C., Lajpat Rai and Rawat, H.S. (1988). Biomass production and its distribution by *Acacia nilotica* plantations at five different ages in Haryana. *Indian Forester* 114, 770-5.

Tesfaye Abebe (1994). Growth performance of some multipurpose trees and shrubs in the semi-arid areas of southern Ethiopia. *Agroforestry Systems* 26, 237-48.

Thompson, K.T. (1992). Prickly acacia infestation of the Mitchell grasslands. Final report: National Soil Conservation Programme. Richmond Landcare Group, Richmond, Queensland.

Tiedemann, A.R. and Klemmedson, J.O. (1973). Nutrient availability in desert grassland soils under mesquite (*Prosopis juliflora*) trees and adjacent open areas. *Soil Science Society of America Proceedings* 37, 107-10.

Tiedemann, A.R. and Klemmedson, J.O. (1986). Long-term effects of mesquite removal on soil characteristics: I. Nutrients and bulk density. *Soil Science Society of America Journal* 50, 472-80.

Tybirk, K. (1989). Flowering, pollination and seed production of *Acacia nilotica*. *Nordic Journal of Botany* 9, 375-81.