ECONOMIC BENEFITS TO PAPUA NEW GUINEA AND AUSTRALIA FROM THE BIOLOGICAL CONTROL OF BANANA SKIPPER (*ERIONOTA THRAX*)

ACIAR Project CS2/1988/002-C

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Abstract

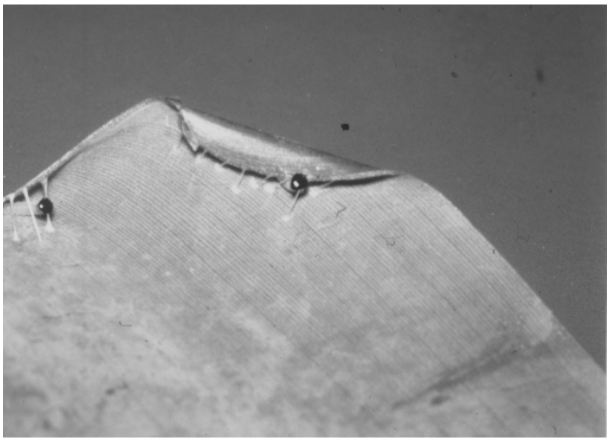
Larvae of the butterfly *Erionota thrax*, the banana skipper, destroy the leaves of bananas by eating them and forming massive protective rolls of leaf tissue. They were first observed in north-western Papua New Guinea in 1983 and over the next 6 years spread throughout the mainland at the rate of up to 500 km/year. *E. thrax* has also spread across the ocean to the east, to invade New Britain, Duke of York and New Ireland islands, and possibly Bougainville.

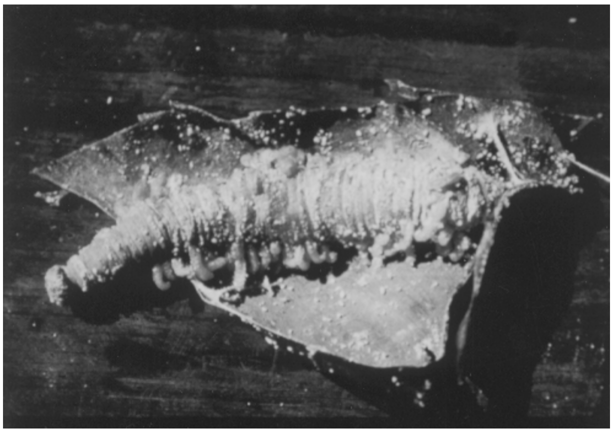
As the banana skipper spread, it destroyed an average of some 60% of banana leaves, leading to both a serious delay in fruit maturation and reduced weight of banana bunches. Previous successful biological control of *E. thrax* when it invaded Mauritius, Hawaii, Guam and Saipan encouraged Papua New Guinea to launch an approach to ACIAR for funds. This was successful and a project was undertaken from 1988 to 1990. After careful tests to ensure that it was safe to do so, the larval parasite *Cotesia erionotae* was introduced and established, leading to a reduction in the estimated average leaf damage from about 60% to 5%.

Using the estimated production value of bananas in Papua New Guinea to the year 2020, the losses due to banana skipper each year were calculated. Using a discount rate of 5%, the net present value of lost production amounts to approximately A$301.8 million. The value of damage prevented by biological control is estimated at $201.6 million.

The reduction of banana skipper abundance by 90% in southern Papua New Guinea has correspondingly reduced the chance of adults invading not only Australian islands in the Torres Strait but also the Australian mainland. The successful biological control program in Papua New Guinea has therefore provided significant benefits to banana production in Australia. Assuming similar levels of damage in Australia as in Papua New Guinea, we estimate these benefits to be $223 million to the year 2020.

The present value of total benefits from the ACIAR project equals $424.7 million ($201.6 million to Papua New Guinea and $223.1 million to Australia). This compares with the present value of the cost of the ACIAR project of $0.70 million, giving a benefit–cost ratio of 607 and an internal rate of return of 190%.





Clockwise from top left:
Erionota thrax butterfly; *E. thrax* leaf rolls on banana leaf; typical damage to banana plantings *before* establishment of *Cotesia erionotae* parasite; banana plantings *after C. erionotae* established; *C. erionotae* larvae emerging from parasitised *E. thrax*; *E. thrax* larvae starting leaf rolls.
[Photos by D.P.A. Sands.]

1. The ACIAR Project

The banana skipper *Erionota thrax* is a butterfly native to South-East Asia. In its native environment the banana skipper is controlled by natural enemies and does little commercial damage. In regions where natural enemies are absent, *E. thrax* can be a significant pest. Its larvae are continuous feeders on banana leaves resulting in defoliation, reduced fruit yields and delayed maturation.

E. thrax was first recorded in Papua New Guinea in 1983. Over the next 5 years, it rapidly established itself as a major pest of bananas throughout the country. Bananas are an important food crop in Papua New Guinea, grown widely in home gardens as a subsistence food and for trade in local food markets.

Soon after its discovery in Papua New Guinea, the very favourable prospects for its biological control, based on results in other countries, were outlined in a dossier that was made available then, but published some time later (Waterhouse and Norris 1989). With the benefit of this background on the skipper and its control prospects, the Papua New Guinea government approached ACIAR for support for a classical biological control project involving collaboration with the Division of Entomology, CSIRO. The serious and increasing damage already being done to bananas in Papua New Guinea, the rising threat of the skipper invading Australia, the overseas successes with biological control of *E. thrax*, the key involvement of two very experienced entomologists (F.M. Dori of Papua New Guinea and D.P.A. Sands of CSIRO) and a very modest budget all contributed to speedy ACIAR funding.

The result was ACIAR project CS2/1988/002-C, which ran from 1988–89 to 1990–91. The project had the following objectives:

- monitor banana skipper populations and damage at selected sites in Papua New Guinea before introduction of exotic natural enemies;
- identify natural enemies attacking banana skipper life stages in Papua New Guinea at present;
- arrange host-specificity testing of relevant exotic parasitoids against appropriate Hesperiidae and representatives from other important families, and seek clearance for release of any that are adequately host specific against banana skipper;

- arrange mass production and release of parasitoids approved for liberation; and

- monitor effects on banana skipper populations after release of exotic natural enemies.

Lim and Hill (1992) in their review of ACIAR project CS2/1988/002-C concluded that all objectives of the original project had been met. The project led to the successful introduction of a biological control agent *Cotesia erionotae* to Papua New Guinea. This agent has significantly reduced the loss in banana production.

This Report

The focus in this report is on the economic benefits of the project relative to the costs. The benefits in the first instance accrue to Papua New Guinea—through mitigation of the loss of banana production that *E. thrax,* if not controlled, would otherwise have caused. But there are also potential benefits to Australia. *E. thrax* spread rapidly throughout Papua New Guinea from the north coast to Port Moresby and islands to the east of the mainland. Biological control in Papua New Guinea has reduced the *E. thrax* population and lowered the probability of spread across Torres Strait to Australia. Furthermore, research conducted during the project has shortened the lead time for clearance testing of a biological control agent if the banana skipper were to enter Australia.

This report represents the third economic evaluation of net benefits of the biological control of the banana skipper in Papua New Guinea. Earlier evaluations are contained in Lubulwa and McMeniman (1997) and Adamson and Davis (1998). The present report is based on more accurate biological assumptions than used in the two previous evaluations.

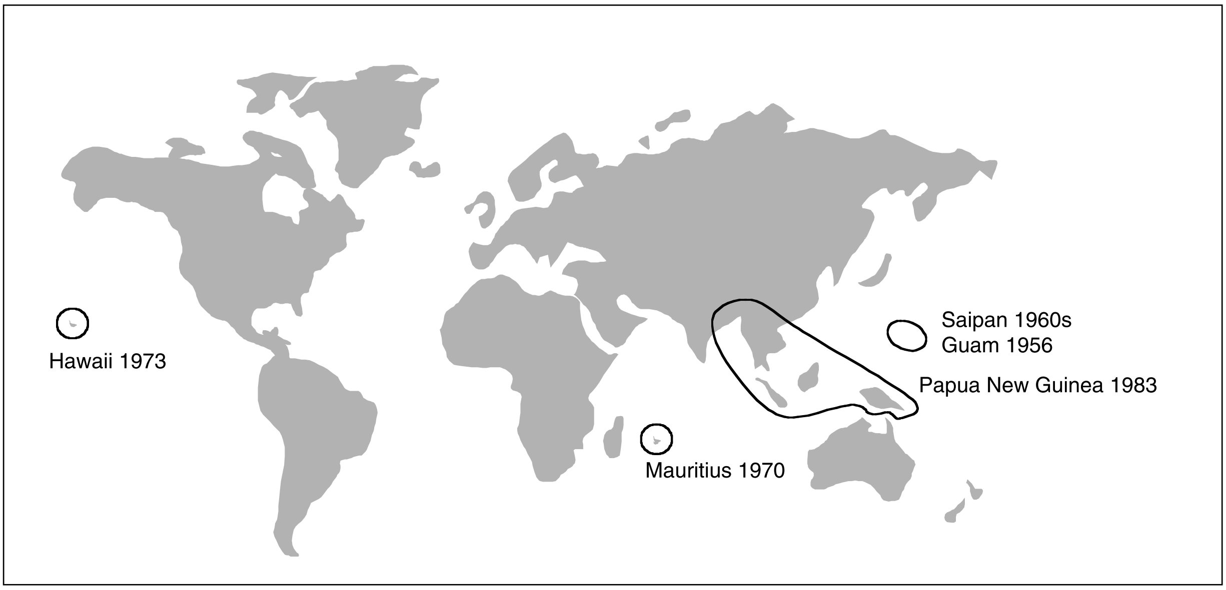
2. The Banana Skipper, Control Agents and Leaf Damage

The Banana Skipper

E. thrax is a highly successful member of the most primitive family of butterflies, the Hesperiidae. It is native to South-East Asia (Figure 1) from where it spread to Mauritius (1970), Hawaii (1973), Guam (1956), Saipan (late 1960s) and Papua New Guinea (1983) (Arura 1987; Sands et al. 1991, 1993; Waterhouse 1991; Waterhouse and Norris 1989).

In its native home it is a widespread but usually uncommon insect, and it is not considered to be of much economic significance. This is believed to be because it is widely attacked in the egg, larval and pupal stages by a number of parasitic wasps and flies and, to a lesser extent, by predators. After the establishment of *E. thrax* in Mauritius, Hawaii, Guam and Saipan, it was brought under biological control by the establishment, from Malaysia or Thailand, of the egg parasitoid *Ooencyrtus erionotae* Ferrière and the larval parasitoid *Cotesia erionotae* Wilkinson (Waterhouse and Norris 1989).

Figure 1. World distribution of *Erionota thrax*



The female banana skipper lays her eggs at dusk or early dark, either singly or in groups of up to about 25, mostly on the lower surface of the host leaf. The larva hatches 5–8 days later and immediately proceeds to the edge of the banana leaf where it begins to roll and tie the leaf into a shelter from which it feeds on leaf tissue. Larval development takes 23–32 days according to the temperature, and adults may live up to 5 months. If there is a single larva on a leaf, it often starts its roll near the leaf apex. As it grows, it forms a roll towards the midrib, after which it returns to near the apex and repeats the rolling process on the opposite side of the midrib. If there are several larvae on the same leaf, a larva rolls and ties a portion of the leaf until it approaches the roll of another larva, whereupon it abandons its roll and proceeds to another portion of the leaf or to another leaf to commence another roll. The amount of leaf tissue inactivated by the leaf rolls is vastly greater than the amount consumed.

All except first instar larvae are covered with a whitish waxy powder, some of which is transferred to the inside of the leaf roll. The waxy powder increases in amount as the larva develops. Heavy rain causes high mortality of young larvae due to their lack of protective waxy powder and inadequate protection from their first leaf rolls. Older larvae close their rolls more securely and produce enough waxy powder to be water-repellent (Waterhouse and Norris 1989). Shredding of the banana leaves by high winds prevents normal leaf rolling and may lead to high mortality of young larvae.

Adults usually emerge in the afternoon and fly powerfully and apparently erratically about banana plants in the early evening and early morning. They are frequently attracted to light. Lights in boats and loading aircraft may attract adults, assisting movement to uninfested areas. In South-East Asia there are five generations a year and the same is probable in other favourable environments. In Papua New Guinea, *E. thrax* occurs on *Musa* spp., *Australimusa* spp. and *Eumusa* spp., which are widespread in native forests (Sands et al. 1991). The only direct damage caused by it is to the leaves, which are rolled and eaten. The fruit is not damaged.

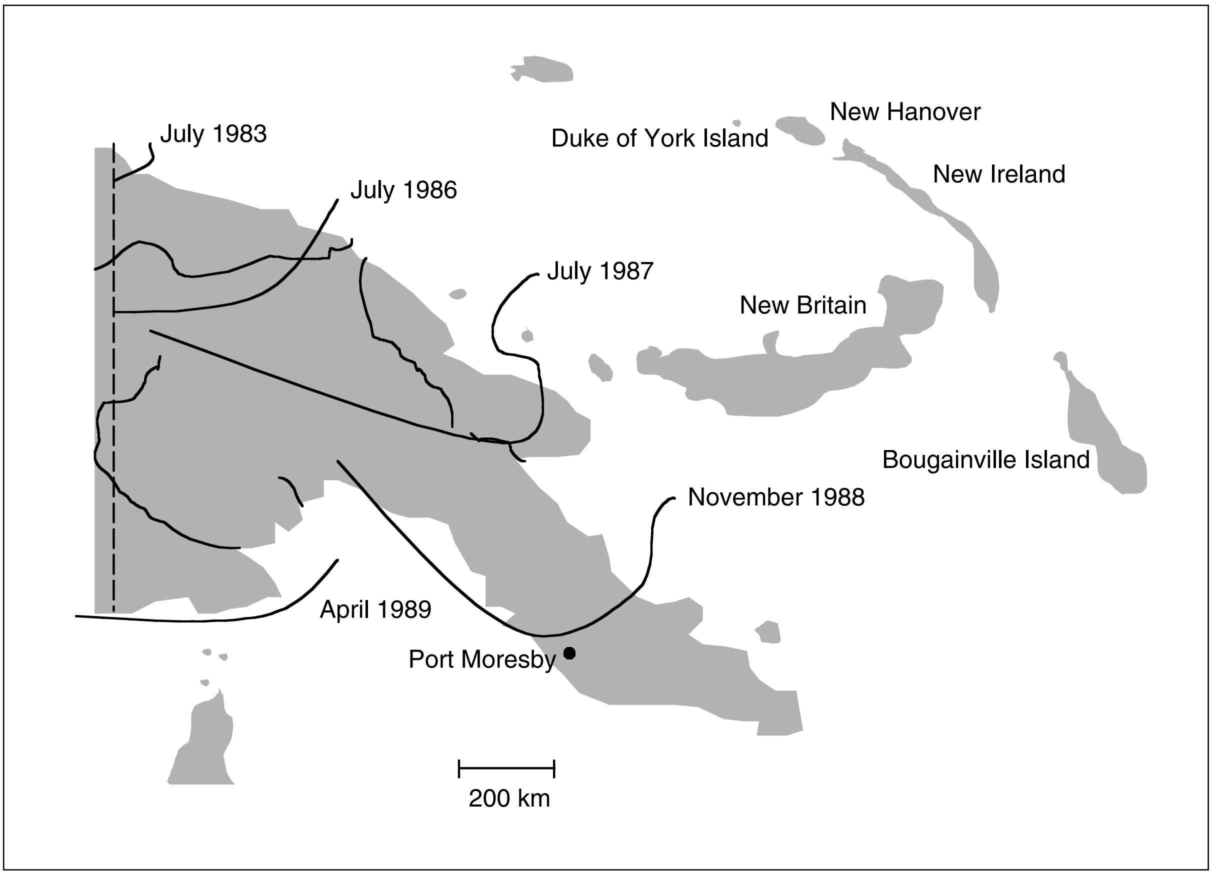
Banana leaves are not the only host of E. thrax

The other economic host of the banana skipper in Papua New Guinea is Manila hemp (*Musa textilis* Nee), although this crop is of quite minor value compared with bananas. It is nevertheless a crop with potential in the future for Papua New Guinea agriculture. The ornamental native species *Heliconia papuana* is a widespread host for *E. thrax* (F.M. Dori and D.P.A. Sands, pers. comm.).

The Colonisation of Papua New Guinea by *E. thrax*

The banana skipper is known to have been present in Irian Jaya for some years before it was first collected (in August 1983) at Vanimo in north-western Papua New Guinea (Arura 1987). By July 1986 it had spread to East Sepik Province and by mid-1987 it was defoliating banana plants in Madang and Morobe provinces (Sands et al. 1991). Since then, *E. thrax* has become established at altitudes up to 2500 m in Eastern Highlands Province, up to 2060 m in the Finisterre Ranges and in all coastal areas, including by 1989 the Western Province, less than 5 km from the Australian Torres Strait island of Boigu (Figure 2). Once the skipper population built up in north-western Papua New Guinea, it spread throughout the rest of mainland Papua New Guinea at a rate of up to some 500 km a year, including through what might have been assumed to be somewhat inhospitable highland jungle.

Figure 2. Establishment and spread of *Erionota thrax* in Papua New Guinea. Source: Sands et al. (1991)



By March 1992 it had reached Rabaul, East New Britain, where defoliation of 62% was measured in some newly invaded localities. In surveys carried out in 1988 and 1989, the maximum number of leaves carrying leaf rolls was 94% at Bulolo in Morobe Province. Although plants were frequently defoliated, the highest average level of defoliation at any one site was 70% near Busa in the Markham Valley (the average overall was 30%) and the maximum number of leaf rolls was six per leaf at Goroka in Eastern Province. Even as few as two larvae per leaf resulted at several localities in plants being completely defoliated, leaving only leaf stalks. It is significant that the egg parasitoid *Ooencyrtus erionotae* was present at all of the defoliated sites and had an overall parasitisation of about 29% (Sands et al. 1991).

The skipper is threatening to spread along the island chain into the northern Solomon Islands and into the western Pacific. It is known that, after its arrival in Oahu, Hawaii in 1973, the skipper spread in the next two or three years to the other islands in the group over water distances up to 150 km (Waterhouse and Norris 1989). A water barrier of lesser magnitude would not inhibit entry into Torres Strait or the northern Solomon Islands.

The higher the banana skipper population in Papua New Guinea, the greater the chances that a successful colonising flight will occur. By 1994 New Britain, the Duke of York and New Ireland islands to the east of the Papua New Guinea mainland had been infested and there have been unconfirmed reports of its presence on Bougainville (F.M. Dori and D.P. Sands, pers. comm.). Population reduction of *E. thrax* is the key to minimising the risks of unaided intrusion into new areas.

How *E. thrax* entered Papua New Guinea is not established. It might well have flown from eastern Irian Jaya, or eggs or young larvae might have been carried across the border on banana leaves used for wrapping. The fact that the egg parasitoid *Ooencyrtus erionotae* was already present in Papua New Guinea as *E. thrax* spread raises two possibilities:

- either it was already present and widespread on some, as yet unidentified, other host(s); or
- parasitised *E. thrax* eggs were among the eggs involved in the early establishment of the banana skipper in western Papua New Guinea.

Control Agents

In its native range in South-East Asia, *E. thrax* is attacked by a large number of parasitic wasps and flies, and by several predators. Together, these natural enemies, many of which are themselves parasitised, exert a considerable measure of biological control, although from time to time damaging outbreaks may occur (Waterhouse and Norris 1989).

When *E. thrax* appeared in Mauritius in 1970, four parasitoids were introduced, of which two became established (the egg parasitoid *Ooencyrtus erionotae* and the larval parasitoid *Cotesia erionotae*). These two species (and a third *Scenocharops* sp.) were established in Hawaii when the skipper appeared there in 1973. In both countries *E. thrax* was rapidly brought under good to excellent biological control (Waterhouse and Norris 1989). In 1974 *Cotesia erionotae* was introduced to both Guam and Saipan, where satisfactory biological control of *E. thrax* has also been achieved.

In 1988 three parasitoids were reared from *E. thrax* eggs in the Morobe and Eastern Highlands provinces of Papua New Guinea. They were *Ooencyrtus erionotae*, *Ooencyrtus* sp. and *Anastatus* sp. Of these, only *O. erionotae* caused significant mortality, averaging 30%, although it reached 82% on one occasion. Larvae were occasionally attacked by predatory bugs (*Platynopus melanacanthus*), but not parasitised. About 5% of pupae were parasitised by a wasp (*Brachymeria* sp.) and a fly (*Palexorista* sp.) (Sands et al. 1991, 1993). This level of attack did not prevent populations of *E. thrax* attaining levels sufficient to cause highly significant defoliation of banana leaves. The key difference between successful suppression in Mauritius, Hawaii, Guam and Saipan, and totally inadequate suppression in Papua New Guinea, was the absence from Papua New Guinea of the larval parasitoid *Cotesia erionotae*.

Although, after the initial build up in abundance with associated serious defoliation in 1987–88, *E. thrax* numbers appeared to fall in 1990, biological control with the existing natural enemies continued to be ineffective (Sands et al. 1991). In 1992 two additional egg parasitoids were reared (*Ectopiognatha* nr. *major*, *Telenomus* sp.) and birds, particularly crows, were at times seen opening leaf rolls to reach the larvae and pupae. However, by this time the widespread liberation of the larval parasitoid was having a dramatic effect.

Cotesia erionotae females may probe a host larva without ovipositing and may lay more than one egg in a larva, both resulting in unrecorded host mortality. Thus, the 67% of host larvae producing parasitoids 7 months after parasitoids were first released at Laloki in March 1990 (Sands et al. 1993) was probably an underestimate of the mortality occurring even at this very early time of parasitoid colonisation.

Testing for parasitoid specificity

In order to obtain quarantine permission to release *Cotesia erionotae* in Papua New Guinea, it had to be established that it was unlikely to influence the abundance of birdwing butterflies or other species considered to be of importance. This took two years, during which *E. thrax* continued to spread and multiply.

The specificity of *C. erionotae* for *E. thrax* was clearly demonstrated by its characteristic pre-ovipositional display, ovipositional response and the development of offspring. Larvae of two showy birdwings (*Troides oblongomaculatus papuensis* Wallace, and *Ornithoptera priamus poseidon* Doubleday), of the orchard butterfly (*Papilio aegeus ormenus* Guérin-Meneville) — all Papilionidae — and of the far more closely related *Cephrenes augiades websteri* Evans (Hesperiidae) were not attacked (Sands et al. 1993). And there is no evidence that *C. erionotae* has parasitised species other than *E. thrax* since its liberation in Papua New Guinea. The specificity tests were carried out in a special quarantine facility constructed by the project at Laloki, near Port Moresby. This facility still exists to provide quarantine conditions for other investigations.

Preliminary tests were also carried out on the larvae of five species of large Australian Hesperiidae to determine whether they would be attacked by *Cotesia erionotae*. These tests were in anticipation of AQIS requirements should *E. thrax* arrive in Australia, necessitating biological control.

▶▶▶▶ Hesperiidae

■ Pyrginae

Euschemon rafflesia (Macleay)

Chaetocneme beata (Hewitson)

■ Trapezitinae

Trapezites symmomus (Hübner)

■ Hesperiinae

Cephrenes trichopepla (Lower)

Cephrenes augiades (Felder)

The first two species are very primitive. The third is the largest Australian skipper in the subfamily Trapezitinae, approaching *E. thrax* in size. The two *Cephrenes* species belong to the same subfamily (Hesperiinae) as *E. thrax* and are thus more closely related than either of the others. *Cotesia erionotae* did not display its characteristic oviposition behaviour or attack the larvae of any of these species (Sands, pers. comm.).

Less is known of the specificity of the egg parasitoid *Ooencyrtus erionotae* which, like *C. erionotae*, is not recorded from hosts other than *E. thrax* in Papua New Guinea. Its behaviour is disrupted by confinement within cages so that false positive reactions are encountered to eggs of species that would not be attacked in the field (Sands 1993). Thus, *Ooecyrtus erionotae* completed development in the laboratory in the eggs of *Cephrenes augiades*, showing that it will attack other hosts when confined in an artificial environment. However, eggs of the related *Cephrenes mosleyi* were never attacked in Papua New Guinea, even when present on different host plants when *E. thrax* eggs were being attacked nearby.

The relevance of the testing on Australian Hesperiidae to the economic analysis presented later is that, if *E. thrax* is discovered on Australian soil, permission would have to be obtained from quarantine (AQIS) to liberate any exotic parasitoids. Two factors would be crucial before permission was granted:

- the time taken by the more than 20 authorities involved in advising AQIS on whether to grant permission on existing specificity information or whether to require additional tests and, if so, on which species (delays of some months are not unusual); and

- the time taken to carry out additional tests, if any (this might occupy 6–24 months, depending upon the availability of the larvae of nominated non-target species).

Effects of Leaf Damage

The banana plant (*Musa acuminata* Colla, *Musa balbisiana* Colla, *Musa sapientum* L.) is a pseudostem, which arises from a rhizome (corm) situated at ground level. It is propagated vegetatively by planting 2–4 kg rhizomes, 2.5–3.5 m apart. Suckers grow from the corm. One is selected to form the next fruit-bearing pseudostem and the others are excised. The selected sucker grows to a height of 2–4 m and, at about weekly intervals for 30 weeks, the pseudostem puts on another leaf. At approximately 210 days a fruiting bud emerges near the apex and this develops steadily to produce, after a further 90–120 days, a bunch of bananas. Thus, depending upon banana variety (of which there are many) and growing conditions, a bunch of bananas is produced by each rhizome about every 300 days.

Leaves fall at the rate of one in every 10–12 days so that, when the fruiting bud emerges at the top of the pseudostem, the plant has an average of 15 leaves and no new leaves are produced thereafter. The oldest leaves continue to fall until, at harvest, the plant has 6–8 leaves.

At harvest, the bunch is removed, the pseudostem is severed at the base and, at the same time, another sucker is selected to produce the next pseudostem. The production of bananas is thus a continuous process with plants at all stages of bearing fruit. A commercial crop is usually harvested daily (Ostmark 1974).

Any factors that:

- reduce the weight of bananas produced;
- extend the time required for a bunch to mature; or
- impair banana leaves for traditional uses

will result in losses.

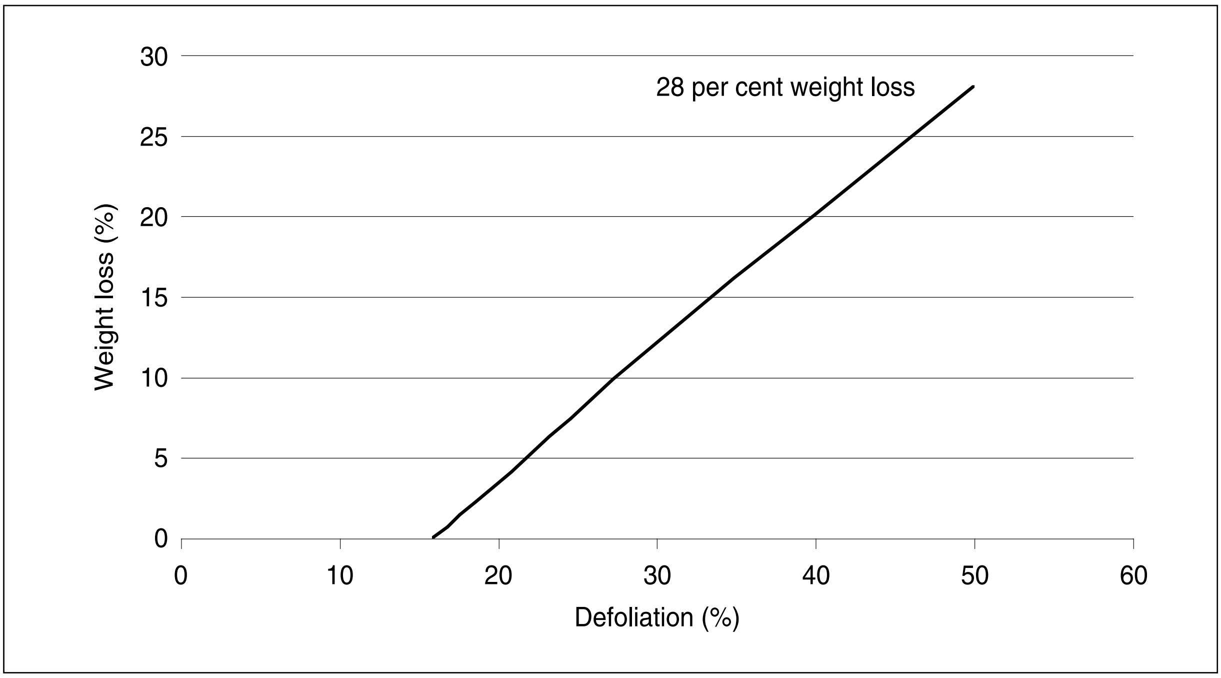
The banana plant has been said to produce leaves in excess of its need for fruit production. This was concluded because bananas defoliated to the extent of 0, 10, 20, 30 and 40% at 35-day intervals for 4 years showed no significant loss in fruit weight until 20% or more leaf area had been removed (Ostmark 1974). Defoliation at the time of appearance of the fruiting bud caused the greatest reduction in fruit weight. Fifty per cent defoliation at this time caused 28% weight loss (Hartman and Bailey 1929). In New South Wales, Turner (1970) found that the yield of Williams variety bananas was not significantly reduced until only three leaves remained at the time that the fruiting bud emerges. Ostmark also quoted the work of Anon. (1951) on Dwarf Cavendish bananas in French Guinea in which a linear relationship was established between yield and leaf number over the range of 11–16 leaves at bud emergence. In New South Wales, bananas rarely have more than 12 leaves at this time.

A major factor that is easy to overlook in the Ostmark experiment is that defoliation by *E. thrax* larvae is continuous and does not occur only at 35-day intervals. In his experiments, following any one defoliation, four new leaves will have appeared before the next defoliation, one each at weekly intervals. Three of these leaves, at least, will have substantially expanded to full size and the fourth partially so. Three of the defoliated leaves (1 every 10 days) will have senesced and thus will have contributed less than their percentage defoliation to any reduced yield.

Taking the figure of 15 leaves per plant at fruiting bud emergence and three undamaged leaves being present for much of each 35-day interval, it would be logical to reduce the Ostmark defoliation percentages by 20% (3/15). This means that an artificial defoliation at 35-day intervals of 20% would equate to *E. thrax* continuous defoliation of 16%. The relationship between percent defoliation and percent weight loss is shown in Figure 3.

An equally critical factor that is easy to overlook is the significantly greater length of time required for the bunch to reach maturity even at leaf losses less than 20%. Experimental data from Papua New Guinea and Australia to enable this period to be accurately determined appear not to be available, but an informal estimate is that maturation may be delayed by a month or two (Sands, pers. comm.).

Figure 3. The relationship between percentage defoliation and reduction in weight of bunch at harvest



3. Project Costs and Benefits

ACIAR provided the main source of funding for the project. These costs were incurred over the period 1988 to 1990. As a result of ACIAR project outlays, the project has led to a stream of financial benefits to Papua New Guinea and also to Australia. These benefits accrue from the time the biological control agent was introduced for as long as it provides effective control of the banana skipper. The experience with biological control agents in other situations has been that, once established, they maintain their effectiveness from year to year. There is no evidence to indicate that the effectiveness of the biological control agent will decline in the future. We therefore estimate benefits over a relatively long period — to 2020.

In comparing benefits with costs we need to convert the stream of historic costs and future benefits to present value terms. We use a discount rate of 5% to do this.

Costs

The main project outlays, by ACIAR, are shown in Table 1. Some additional costs have been incurred by CSIRO on project research, the use of quarantine facilities in Brisbane and distributing *Cotesia erionotae* to newly infested areas of Papua New Guinea since 1990, and by the Papua New Guinea Government. It is estimated that Papua New Guinea's contribution was about 5% of the ACIAR costs and CSIRO's contribution about 10% of the ACIAR costs. Total ACIAR project costs are $701 000 in present value (1999) terms.

Table 1 ACIAR project outlays—1990 prices

Year	$
1988	171 119
1989	254 661
1990	82 065
Total	507 845
Present value in 1999 (5% discount rate)	**700 621**

These costs are low in absolute terms. This is because the project was able to draw on the results of longer term research on the problem. That research had identified the appropriate control agent and its likely success rate. The ACIAR project could therefore be restricted to adoption and testing.

Benefits to Papua New Guinea

The benefits to Papua New Guinea from biological control of banana skipper in Papua New Guinea represent the difference between the time path of banana production value with the control agent present and the time path of production assuming no control agent. This is illustrated schematically in Figure 4.

Figure 4. Schematic representation of stream of benefits to Papua New Guinea

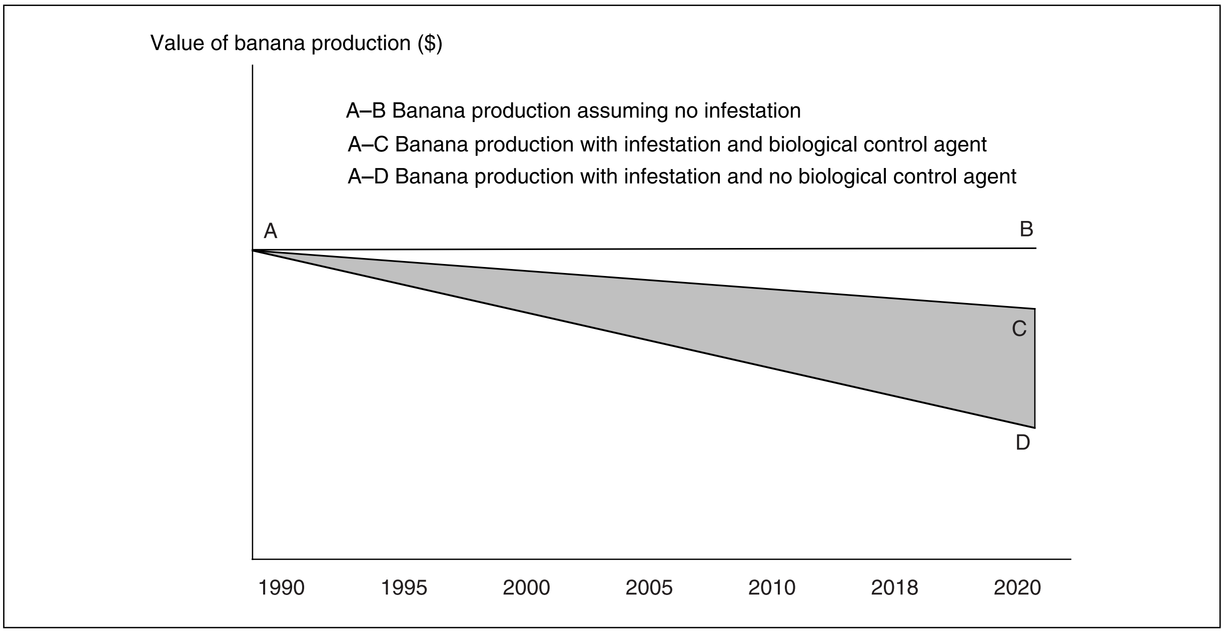


Figure 4 shows three lines. The line AC represents banana production with banana skipper infestation and the biological control agent. The line AD represents banana production with banana skipper infestation and no biological control agent. The difference between the two lines represents the value of banana production 'saved' by the control agent and hence the benefits from the control agent. The line AB indicates banana production assuming no infestation of banana skipper. Since the skipper has been in Papua New Guinea since 1983, this line is hypothetical. Its inclusion is important, however, as it illustrates that even with successful biological control there is still some loss of production from the pre-infestation situation.

To calculate the benefits to Papua New Guinea of the control agent, we first need to generate values for the lines AB, AC and AD.

Banana production in Papua New Guinea

Bananas are a key subsistence food crop in Papua New Guinea. They are the dominant staple or a staple crop in most farming systems across the provinces. At least 8% of the people of Papua New Guinea obtain more than 60% of their daily calorie intake from bananas and banana consumption among many of the remainder is very high (M. Burke, pers. comm.; F. Dori, pers. comm.).

The banana crop is second in importance only to that of sweet potato. More than 60 cultivars of bananas are grown, about half a dozen of which are important (Sands et al. 1991). In addition to food, banana leaves are used extensively for weaving baskets, protection of food from flies, wrapping food for market and for cooking, tablecloths, temporary mats, protection of fruit from bats and birds during ripening, and protection of firewood from rain. There are no substitutes in many localities and some of these uses have traditional social significance. All consumption is met from domestic production.

The Food and Agriculture Organization (FAO) provides statistics of banana production and consumption for food in Papua New Guinea (Table 2). The statistics indicate banana production of 600 000 t in 1991, the year when the biological control agent became effective throughout the infested areas. The FAO estimates assume 10% of production is wasted and a further 10% is fed to animals — that is, 80% of production is consumed as human food.

Table 2. Estimates of banana production and consumption in Papua New Guinea

Year	Production ('000 t)	Production consumed as food ('000 t)
1990	600	480
1991	600	480
1992	625	500
1993	640	512
1994	640	512
1995	650	520
1996	665	532
1997	450	360
1998	450	360

Source: Food and Agriculture Organization, Rome.

The FAO estimates imply an average banana consumption in Papua New Guinea of 127 kg/head in 1991 and 84 kg/head in 1998. These estimates appear high, though they may still be plausible. Brown (1984) refers to banana consumption of about 4.5 kg/head/day, of which 2.7 kg is edible matter, in some African countries where bananas form the staple food. This is much higher than the estimates for Papua New Guinea.

The reliability of the FAO statistics has been questioned by crop scientists. In Papua New Guinea, plantings are in many, small garden plots throughout widely scattered villages rather than as monoculture plantations. And yields differ significantly between plots. This makes production extremely difficult to estimate. The FAO relies for its information on an annual production questionnaire sent to the Papua New Guinea Department of Agriculture and Livestock (DAL). However, DAL does not itself undertake work to estimate annual production.

Projecting future Papua New Guinea banana production volume and value

We would expect that population growth by itself will put upward pressure on banana production. But growth in per capita incomes through economic development will exert downward pressure on per capita banana consumption through providing increased access to a wider array of foods.

We assume an average annual rate of population growth in Papua New Guinea to 2020 of 1.8%. This estimate comes from the United Nations' population projections framework. If there were no change in per capita incomes, a reasonable assumption is that banana production would expand in line with population growth. We anticipate growth in per capita income in Papua New Guinea of about 0.6% per year through to 2020 — that is, a continuation of the poor per capita growth experience of the 1980s and 1990s. We do not therefore expect much decline in per capita banana consumption. Between 1990 and 1996 banana consumption declined by about 0.15% per year. We assume a similar rate of decline to 2020. These assumptions imply annual banana production growth of about 1.7% per year.

As noted earlier, most bananas grown in Papua New Guinea are not traded in the marketplace—they are consumed by the families that grow them. In this situation the value of bananas to the population represents the value to them of the next best alternative food to bananas. Sufficient bananas are, however, bought and sold in local markets to obtain an estimate of their value to Papua New Guinea citizens.

Average prices of green and eating bananas on the hand in urban centres (Port Moresby, Goroka, Lae, Madang, Rabaul) for cooking bananas and eating bananas are collected quarterly by the National Statistics Office (Table 3). The prices refer to cooking bananas and eating bananas. Our understanding is that about 70% of consumption is cooking bananas and 30% eating bananas.

We calculate an average market price of bananas across all markets shown using these weights and the sales shares of the total accounted for by each market's sales. The result for 1997 is an average price of 0.87 kina/kg, which represents A$0.82/kg.

Next, we need to filter these prices of their transport, and wholesale and retail sales margin elements to get an estimate of the average price to producers. The data indicate a large spread of prices between markets such as Port Moresby, where transport and other margins are known to be high, and markets such as Madang where the reverse is true. For example, in the first quarter of 1998, the market price of cooking bananas was 1.73 kina/kg in Port Moresby, whereas in Madang the price was only 0.34 kina/kg. The weighted urban average price in this period was 1.08 kina/kg.

Table 3. Average prices of bananas in local markets—nominal prices

Year	Cooking bananas (Kina /kg)	Eating bananas (Kina /kg)	Weighted average (Kina /kg)
1990	0.569	0.375	0.512
1991	0.537	0.439	0.508
1992	0.578	0.449	0.539
1993	0.603	0.440	0.554
1994	0.595	0.441	0.549
1995	0.599	0.530	0.578
1996	0.581	0.517	0.562
1997	0.919	0.754	0.870
1998 (average of first three quarters)	1.102	0.832	1.021

Source: National Statistics Office, Papua New Guinea.

Our inquiries suggest that, on average across all centres, about 60% of the market price is made up of margins between the point of production and point of sale. Because of the large subsistence element in Papua New Guinea banana production and the lack of market opportunities for many growers, determining the average price of bananas to producers is not straightforward. For producers within easy reach of markets, this value will relate directly to the market price. Trade opportunities are often restricted by poor roads and postharvest handling conditions which would result in large transport losses.

For growers lacking market access, the value they place on bananas will reflect the costs and effort they incur in obtaining another source of food to replace bananas. For some producers, banana-growing land is not scarce. Producers could compensate somewhat for banana skipper damage by planting more land to bananas.

Because of these considerations, we have adjusted downward the estimate of the value of bananas to producers to 10% of the market price. This yields a value of bananas to producers in 1997 of 0.087 kina/kg, equivalent to 8.2 cents Australian/kg.

The real price of bananas to producers can be expected to fall over the longer term. This is the usual experience with agricultural commodities in developing and developed economies. We assume a real price decline of 2% per year. The resultant baseline projections for banana production, consumption as food and gross value of production assuming no banana skipper infestation are shown in Table 4. In calculating the gross value of production series we have included only production consumed by persons. We have not attached a value to production consumed by livestock.

Estimation of banana production loss

From about 1986 to at least 1990, when the first release of *Cotesia erionotae* was made, the damage caused by *E. thrax* larvae in Papua New Guinea increased rapidly as their distribution and abundance increased. An average figure of 60% defoliation was quoted for 1992 for an area where the parasitoid was not yet present (Sands et al. 1993).

Defoliation by the skipper causes both a delay in fruit maturation and a loss in bunch weight. There are no empirical estimates of the effects of banana skipper leaf damage on Papua New Guinea banana production in the period before biological control was introduced. Fieldwork measurement of damage was not undertaken. Qualitative observations were, however, made of the extent of leaf damage. Leaf damage was extremely severe—up to 70 per cent defoliation—in the higher rainfall areas where the diploid varieties of bananas are grown. Damage was extensive, though not as high, in the drier areas where the hardier triploid bananas are grown. Based on these estimates of leaf damage, we have assumed a banana production loss of 30%. Using the experimental work of Hartman and Bailey (1929) and Ostmark (1974) on the relationship between degree of defoliation and reduction in weight of bunch at harvest, and after accounting for maturation delays, we can also synthesise conservative estimates of production loss from skipper defoliation of around 30%.

Table 4. Baseline projection of Papua New Guinea's banana production, consumption as food and gross value of production to 2020. Unshaded area, actual; shaded area, projected

Year	Production ('000 t)	Consumption ('000 t)	Price[a] (real 1999 A$/t)	Gross value of production to producers $m (1999 prices)
1990	600.0	480.0	139.2	66.8
1991	600.0	480.0	129.9	62.3
1992	625.0	500.0	141.5	70.8
1993	640.0	512.0	141.9	72.7
1994	640.0	512.0	98.1	50.2
1995	650.0	520.0	83.1	43.2
1996	665.0	532.0	68.5	36.5
1997	450.0	360.0	99.0	35.6
1998	450.0	360.0	79.7	28.7
1999	457.6	366.1	78.1	28.6
2000	465.4	372.3	76.6	28.5
2001	473.2	378.6	75.1	28.4
2002	481.2	385.0	73.6	28.3
2003	489.4	391.5	72.1	28.2
2004	497.7	398.1	70.7	28.2
2005	506.1	404.9	69.3	28.1
2006	514.6	411.7	68.0	28.0
2007	523.3	418.7	66.6	27.9
2008	532.2	425.8	65.3	27.8
2009	541.2	433.0	64.0	27.7
2010	550.4	440.3	62.8	27.6
2011	559.7	447.7	61.5	27.5
2012	569.2	455.3	60.3	27.5
2013	578.8	463.0	59.1	27.4
2014	588.6	470.9	58.0	27.3
2015	598.5	478.8	56.8	27.2
2016	608.7	486.9	55.7	27.1
2017	619.0	495.2	54.6	27.0
2018	629.4	503.5	53.5	27.0
2019	640.1	512.1	52.5	26.9
2020	650.9	520.7	51.4	26.8

[a] *Assumes 10 per cent of market price.*

Using the production value projections, which take into account changes in production quantity and price to producers to 2020, we can then calculate expected losses due to the banana skipper each year until 2020. These are shown in column 2 of Table 5. Using a discount rate of 5%, the net present value of the lost production is approximately $301.8 million.

The effectiveness of biological control increases for several years as parasite abundance builds up. The percentage damage reduction is assumed to be zero in 1990, building up according to the schedule in column 3 of Table 5 to a peak of 95% in 1995. That is, we assume that it has taken 5 years for *Cotesia erionotae* to be distributed to all banana-growing districts and to attain its eventual high level of effectiveness.

We estimate the value of the biological control to Papua New Guinea by calculating the value of damage that is prevented by biological control. This is simply the percentage estimate of effectiveness of the biological control multiplied by the potential losses due to the banana skipper. The present value of these losses (to 2020), and hence the value to Papua New Guinea of the biological control project, is $201.6 million.

It is typical of successful biological control that the pest is not eliminated, although it may be reduced from time to time to such a low level locally that a specific (or nearly specific) parasitoid is unable to survive because it cannot locate hosts. When this happens, the pest is able to reproduce freely for one or more generations until the parasitoid returns to the area and begins attacking its host again. Thus, there are typically (and this occurs in *E. thrax*) restricted local areas where, from time to time, pest abundance rises briefly to damaging levels before being brought under control.

Assuming a peak 95% damage control, the percentage defoliation from the skipper is still significant. That is, in spite of biological control, Papua New Guinea still continues to suffer the production value losses shown in column 5 of Table 5. The present value of this loss is $96.6 million, which is the difference between the $301.8 million of lost production from skipper damage and the $201.6 million of damage prevented by biological control.

The Value to Australia of the ACIAR Project

Australia has a flourishing banana production industry centred on north Queensland, but also including the mid-north coast of New South Wales, Western Australia and expanding Northern Territory plantings. In 1997 Australia produced 199 581 t of bananas yielding an average price to producers of $1119/t. The gross value of Australia's banana production was $223.3 million (1997 prices). About 72% of the production was in north Queensland, 19% in northern New South Wales, 7% in Western Australia and the remainder in the Northern Territory.

Table 5. Benefits to Papua New Guinea measured as the monetary value of damage reduction due to biological control

Year	Total cost of defoliation ($m)	Percentage damage reduction achieved by biological control (%)	Benefits to Papua New Guinea from biological control ($m)	Production value loss with biological control ($m)
1990	31.1	0.00	0.0	20.0
1991	27.6	0.05	1.4	17.8
1992	29.9	0.20	6.0	17.0
1993	29.2	0.70	20.4	6.5
1994	19.2	0.90	17.3	1.5
1995	15.8	0.95	15.0	0.6
1996	12.7	0.95	12.0	0.5
1997	11.8	0.95	11.2	0.5
1998	9.0	0.95	8.6	0.4
1999	8.6	0.95	8.1	0.4
2000	8.1	0.95	7.7	0.4
2001	7.7	0.95	7.3	0.4
2002	7.3	0.95	7.0	0.4
2003	7.0	0.95	6.6	0.4
2004	6.6	0.95	6.3	0.4
2005	6.3	0.95	6.0	0.4
2006	6.0	0.95	5.7	0.4
2007	5.7	0.95	5.4	0.4
2008	5.4	0.95	5.1	0.4
2009	5.1	0.95	4.8	0.4
2010	4.8	0.95	4.6	0.4
2011	4.6	0.95	4.4	0.4
2012	4.4	0.95	4.2	0.4
2013	4.1	0.95	3.9	0.4
2014	3.9	0.95	3.7	0.4
2015	3.7	0.95	3.6	0.4
2016	3.6	0.95	3.4	0.4
2017	3.4	0.95	3.2	0.4
2018	3.2	0.95	3.0	0.4
2019	3.0	0.95	2.9	0.4
2020	2.9	0.95	2.7	0.4
Total	**322.7**		**248.6**	
Present value (1999 prices)				
	301.8		201.6	

To calculate the value to Australia of the ACIAR project, we first need to estimate a baseline value of production of bananas in Australia through to 2020 assuming no banana skipper entry to Australia.

Quarantine restrictions, because of disease concerns, ban the import of bananas into Australia. And Australian banana production costs are too high to allow competitive exports on a continuous basis. Growth in Australian banana production is therefore tied to growth in domestic demand for bananas.

We assume that banana consumption in Australia will grow at the rate of increase in population (around 1% per year). We also assume real prices declining by about 2% per year, implying a decline in real gross value of production of around 1% per year. This yields the baseline gross value of production series in column 2 of Table 6.

Potential damage from banana skipper infestation in Australia

If the banana skipper becomes established in eastern Australia, there is every reason to believe that it will spread rapidly (up to 500 km/year) to colonise the major regions where bananas are grown commercially. This is confirmed by simulations with CLIMEX, a dynamic simulation model that enables the prediction of a species distribution based on temperature and rainfall. These simulations, reported in Adamson and Davis (1998) show that the major producing regions in Australia are climatically suitable for the skipper. Only the Western Australian region, which accounts for less than 7% of the total value of Australian banana production, has an unsuitable macroclimate. Further analysis by D.P. Sands (unpublished data) indicates that the microclimate in Western Australian banana plantations is quite satisfactory for damaging populations to establish. There is also reason to believe that the damage caused without effective biological control would be similar to that caused in Papua New Guinea.

Insecticidal control is a potential option, but there is no evidence on its effectiveness. It is not in use commercially in infested areas overseas. For a number of reasons, the likelihood of a spray program being effective is very low unless a very intensive spray program (perhaps involving up to 25 sprays/year) is followed. These reasons are as follows.

- Except for the egg, which is exposed on the underside of the leaf, both larval and pupal stages are sheltered by leaf rolls.
- The banana leaf expands so rapidly that a surface film of insecticide on a leaf rapidly becomes incomplete.

- The hilly terrain where many bananas are grown and the irregular spacing of the plants requires spray application on foot or by air, the latter depositing most spray droplets on the upper (non-egg bearing) surface of the leaf.

- There are other non-commercial hosts in the region.

Handpicking and destroying leaf rolls is an effective measure for destroying larvae and pupae, but extremely labour intensive and thus impractical on any extensive scale.

Without the very significant reduction in abundance of *E. thrax* on the southern shores of Papua New Guinea, there is little doubt that it would have invaded one or more Torres Strait islands within two years (that is, by 1992) and the Australian mainland within a further 2–3 years (that is, by 1995).

If *E. thrax* is discovered on Australian territory, the following sequence is probable.

▶▶▶▶ If the infested area is limited, an immediate attempt will be made to eradicate it by destroying leaf rolls and applying insecticide. Except for islands or a very limited mainland infestation, these measures stand little chance of success, particularly since alternative hosts are likely to support *E. thrax* outside the banana-cropping area.

▶▶▶▶ The possibility of biological control will be explored. As indicated earlier, if quarantine permission is granted immediately to mass-rear and release *Cotesia erionotae*, there will be a delay of perhaps 6 months before the releases are in full swing. If permission is withheld until additional specificity tests are carried out, the delay may easily extend to 18–24 months. Meanwhile, *E. thrax* will have an opportunity to spread at up to 500 km/year.

Table 6 provides calculations of the value to Australia (measured in terms of additional gross value of banana production) of biological control of banana skipper in Papua New Guinea from the ACIAR project. The estimates in the table assume that, without the ACIAR project, the skipper would have arrived in Australia in 1995. They further assume that, because of the 90% reduction in banana skipper population in Papua New Guinea achieved through the ACIAR project, the probability of the banana skipper invading Australia has been reduced to zero.

Table 6. Benefits to Australia (measured as additional gross value of banana production) from banana skipper control in Papua New Guinea—constant 1999 prices

Year	Gross value of banana production in Australia ($m)	Loss to Australian gross value of banana production if no biological control ($m)	Loss to Australian gross value of production if no biological control in Papua New Guinea (value to Australia of ACIAR project)[a] ($m)
1992 (Torres Strait invasion)	379.9	0.0	0.0
1993	401.8	0.0	0.0
1994	259.5	0.0	0.0
1995 (Skipper arrives in Australia)	309.6	4.6	4.6
1996	260.7	23.5	23.5
1997 (Biological control introduced in Australia)	246.2	66.5	63.2
1998	232.5	69.8	55.8
1999	219.6	65.9	19.8
2000	217.8	65.3	6.5
2001	216.0	64.8	3.2
2002	214.2	64.3	3.2
2003	212.4	63.7	3.2
2004	210.6	63.2	3.2
2005	208.9	62.7	3.1
2006	207.1	62.1	3.1
2007	205.4	61.6	3.1
2008	203.7	61.1	3.1
2009	202.0	60.6	3.0
2010	200.3	60.1	3.0
2011	198.6	59.6	3.0
2012	197.0	59.1	3.0
2013	195.4	58.6	2.9
2014	193.7	58.1	2.9
2015	192.1	57.6	2.9
2016	190.5	57.1	2.9
2017	188.9	56.7	2.8
2018	187.4	56.2	2.8
2019	185.8	55.7	2.8
2020	184.2	55.3	2.8
Present value (1999 prices)		987.7	223.1

[a] *Assuming Papua New Guinea type biological control is introduced to Australia as indicated in column 1.*

The second column of Table 6 contains our estimate of Australia's gross value of banana production to 2020. The third column estimates the loss to Australia's banana production from banana skipper invasion in 1995. It assumes that the skipper, once full infestation has occurred, will cause a 30% loss in the value of Australia's banana production. We consider this assumption to be conservative. In the first year of infestation (1995) 5% of the eventual loss of 30% occurs, rising to 30% in 1996, 90% in 1997 and 100% (that is, the full 30% loss) in 1998 and beyond. The figures in the column are computed by applying these percentage losses to the baseline estimate of the gross value of production of Australian bananas in column 2.

With a banana skipper infestation, Australia would implement its own biological control program. As noted above, meeting AQIS protocols might well require at least a 2-year delay in doing so. This is reflected in column 4 of the table, which assumes that biological control is introduced in Australia in 1997. The figures in column 4 further assume that the control agent causes a 5% reduction in banana skipper damage in 1997, rising to 20% in 1998, 70% in 1999, 90% in 2000 and its peak of 95% in 2001. From then on, the percentage damage reduction is maintained at 95%.

The difference between the figures in column 3 (present value of $987.7 million) and column 4 (present value of $223.1 million) of $764.6 million represents the benefits to Australia's banana producers in terms of increased gross value of production from applying biological control in the event of skipper entry. This does not represent the value of the ACIAR project to Australia as, without the project, Australia could introduce its own biological control program.

The value to Australia of the ACIAR project is simply the discounted present value of the losses shown in column 4. Australia is able to avoid these losses if, as we have assumed, biological control in Papua New Guinea has reduced the banana skipper population below the threshold needed for it to arrive in Australia. In 1995 and 1996 the potential period of delay to satisfy AQIS requirements would result in losses amounting to 5% and 30% respectively of 30% of the gross value of Australian bananas in each of these years. The loss in 1997, when the parasite achieves a 5% reduction in damage, is simply 95% of the corresponding loss in column 3. In 1998 the loss is 80% of the corresponding column 3 figure (20% damage reduction achieved). In 1999 the loss is 30%(70% damage reduction) and in 2000 the loss is 10% (90% damage reduction). By 2001, when 95% damage reduction is achieved, the loss is 5% of the corresponding value in column 3.

The present value of the benefits to Australia from the ACIAR project under these assumptions is $223.1 million. These estimates are much lower than those for Papua New Guinea even though the value of banana production in Australia is higher than in Papua New Guinea and the anticipated damage from the skipper and effectiveness of biological control are comparable in the two countries. The main reason for this is the assumption that Australia would implement biological control within 2 years of the skipper's arrival. However, in view of the reduced funding for biological control research in recent years and the increasing opposition in some quarters to biological control methods, this assumption may be too optimistic.

These estimates represent an upper limit on the benefits to Australia. They assume that the ACIAR project has effectively eliminated the prospect of banana skipper entry into Australia through to 2020. This assumption may well be too optimistic.

Without successful biological control in Papua New Guinea, by far the most likely method of *E. thrax* invading Australia was by adult flight. It is reasonable to assume that the chances of *E. thrax* adults doing so are directly related to its abundance in Papua New Guinea. Since water has proved no barrier to flying adults in Hawaii or in eastern Papua New Guinea, and since its rate of spread in Papua New Guinea was up to 500 km/year, it is also reasonable to assume that, without the major reduction in abundance brought about by biological control, the skipper would have spread by adult flight from the nearby mainland within 1–2 years at most to Boigu and other Australian islands close to the heavily infested south-western coast of Papua New Guinea. Furthermore, it is reasonable to assume that it would have reached the Australian mainland within 3–5 years, perhaps sooner. On the basis that its population in Papua New Guinea has now been reduced to 10% of what it was before biological control, the chances of invasion should be reduced proportionately—that is, no more than 10–20 years for Torres Strait islands and 30–50 years for Australia (it has already been without invasion for 9 years).

Of course, at any time, cyclonic disturbance could (as happened in 1998 with the papaya fruit fly) result in adults being swept up in Papua New Guinea and carried to a number of Torres Strait islands. However, as before, the chances of this occurring are directly related to the density of adult *E. thrax* on the relevant portion of the Papua New Guinea mainland.

There is also the possibility of illegal transport of banana leaves, used for wrapping, carrying skipper eggs or young larvae from Papua New Guinea into Torres Strait or even into Australia. Thus, there is some risk that

Australia might be invaded before 2020. If, for example, the probability of skipper entry to Australia is still, say, 5% then the expected benefits to Australia calculated above should be reduced by 5%.

Increase in Gross Value of Banana Production as a Measure of Welfare Benefit

Both the Papua New Guinea benefit estimate (Table 5) and the Australian benefit estimate (Table 6) are expressed in terms of the additional value of production that biological control of the skipper brings to producers. Economic analysis generally measures the welfare benefits from a research project in terms of the increase in producer and consumer surplus generated by the project. This represents the net value of additional production generated which becomes available to support higher consumption. A key issue is the extent to which the measure of additional gross value of banana production can be taken as a measure of the welfare benefit from the project.

In the case of Papua New Guinea, where bananas are produced and consumed mostly for subsistence, we consider that the constant price change in imputed revenue from a reduction in banana production is an appropriate measure of the welfare effect of the skipper. A subsistence farmer has little option but to produce and consume bananas. A reduction in banana production therefore directly results in a real welfare loss. To attach a value to this loss of production we assume that the opportunity cost of the farmer's labour (per unit) is in fact the unit price of bananas. In the absence of a detailed model of subsistence farming, we consider this to be satisfactory. In terms of standard consumer and producer surplus measures, the above is consistent with assuming that supply is totally inelastic and demand is elastic. These are reasonable assumptions for subsistence farmers.

In the case of Australia, where banana production is a commercial enterprise, the extent to which increased gross value of banana production measures the net change in producer and consumer surplus warrants further investigation. To estimate change in producer and consumer surplus requires an accurate knowledge of the demand and supply elasticities for Australia.

We estimate the net change in surplus by calibrating a demand and supply system around 1991 production and prices, after assuming values for the point demand and supply elasticities. The welfare loss from the skipper is then calculated by estimating the shift in the supply curve necessary to achieve the assumed production loss. From the resulting estimates of changes in price, production and consumption, the changes in surplus are calculated in the usual way.

Table 7 presents the present value of the welfare changes for a range of demand and supply elasticities.

Table 7. Present value of the welfare changes

Demand elasticity	Supply elasticity		
	1	1.5	2
–1	409	341	307
–2	307	239	205
–5	245	177	143

Source: Centre for International Economics estimates.

These estimates range from $143 million (combination of high range supply and demand elasticities) to $409 million (combination of low range demand and supply elasticities). Over the longer term, commercial banana production in Australia can be expected to be moderately supply elastic. Most banana production is on highly fertile land with readily available alternative uses such as sugarcane and horticulture. The price elasticity of demand for bananas is also likely to be moderate. Australian consumers have many options to bananas and substitute between fruit options as relative prices change. Under these assumptions, the results in Table 7 yield welfare estimates very similar to our value of production based estimate in Table 6.

Comparing Benefits with Costs

The present value of total benefits from the ACIAR project equals $424.7m ($201.6m to Papua New Guinea and $223.1m to Australia). This compares with a present value of ACIAR project costs of $0.70m, implying a benefit–cost ratio of 607. The internal rate of return on the project is 190%.

Benefits which Have Not Been Quantified

The foregoing analysis has dealt only with the losses caused by banana skipper to the value of bananas produced. As noted earlier, banana leaves are used for a variety of additional uses in Papua New Guinea. A benefit not quantified from the project concerns the value Papua New Guinea derives from access to banana leaves undamaged by the skipper.

Introduction of biological control in Papua New Guinea is also likely to have reduced the incidence of *E. thrax* damage to bananas and banana leaves in Irian Jaya where *Cotesia erionotae* has almost certainly been spreading in the last few years. This benefit, which accrues to Indonesia, has not been evaluated in the analysis, although it may well be of the same order of magnitude as in Papua New Guinea.

Finally, we have not quantified the potential benefits to Papua New Guinea from any expansion in Manila hemp production and hence avoidance of the damage to this crop by the skipper.

4. Conclusion

The estimated benefits from ACIAR project CS2/1988/002-C are extremely high relative to project costs. There are five main reasons for this.

- Bananas are a large and valuable crop in Papua New Guinea, and the banana skipper, if uncontrolled, would cause a severe reduction in the value of the crop.
- The biological control agent, once established, is highly effective in controlling the skipper, achieving a 95% reduction in damage on a perpetual basis.
- Biological control does not add to production costs in Papua New Guinea.
- Bananas are a significant commercial crop in Australia and biological control in Papua New Guinea has reduced the probability of the skipper's entry to Australia, and hence the prospect of substantial damage to the Australian crop, from 100% to close to zero.
- Project costs were extremely low, with the project able to lever off successful research and experience in banana skipper control in other countries.

The results show that this project alone yielded benefits that compare favourably with ACIAR's annual budget for crop protection. They illustrate the very large potential benefits achievable from biological control projects which result in effective control of pests causing substantial damage to valuable crops.

It is important to remember that the estimates of net benefits are sensitive to three key variables:

- the volume of Papua New Guinea banana production;
- the value of these bananas to Papua New Guinea; and
- the extent of banana production loss caused by the skipper.

As has been emphasised in earlier sections, there are considerable uncertainties surrounding the true values for each of these variables and hence the resultant estimate of net benefit.

The lack of accurate knowledge of the volume of bananas grown in Papua New Guinea reflects special circumstances in that country—in particular, the difficulty of measuring production of a highly dispersed and subsistence-based crop and the poor state of statistical records and procedures in that country.

The difficulty encountered in valuing bananas to growers also reflects the important role of bananas as a subsistence, rather than a market crop, and encompasses complex issues about the true opportunity cost to subsistence producers and how it should be determined. There are no unequivocal answers to this.

With the benefit of hindsight, the uncertainty surrounding the degree of damage done by the skipper could have been addressed by devoting project funds to measurement of damage and damage control. This would have at least have removed one of the key uncertainties behind the estimates.

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References

Adamson, D. and Davis, E. 1998. Benefits to PNG and Australia from the biological control of banana skipper (*Erionota thrax*). Unpublished report to ACIAR, CRC for Tropical Pest Management, Brisbane, 25p.

Anon. 1951. Experimentation sur le bananier main en Guinée Française. Institut des Fruits et Agrumes Coloniaux, Bulletin 4.

Arura, M. 1987. Overseas news, Papua news. Bulletin of the Australian Entomological Society, 23, 130.

Brown, J.F. 1984. Bananas in South East Asia and Papua New Guinea, Canberra, ACIAR.

Hartman, A.N. and Bailey, A.L. 1929. The effect of defoliation on banana weights. United Fruit Company Research Bulletin, 118p.

Lim, G.S. and Hill, A.R. 1992. ACIAR project review of PNCS2/1988/002-C: Biological Control in the South Pacific. Canberra, ACIAR.

Lubulwa, G. and McMeniman, S. 1997. An economic evaluation of realised and potential impacts of 15 of ACIAR's biological control projects (1983–1996). Canberra, ACIAR Economic Evaluation Unit Working Paper Series No. 26, 42p.

Ostmark, H.E. 1974, Economic insect pests of bananas. Annual Review of Entomology, 19, 161–176.

Sands, D.P.A. 1993. Effects of confinement on parasitoid/host interactions: interpretation and assessment for biological control of arthropod pests. Proceedings of the 5th Applied Entomological Conference, Canberra, 27 March–1 April 1993, 196–199.

Sands, D.P.A., Bakker, P. and Dori, F.M. 1993. *Cotesia erionotae* (Wilkinson) (Hymenoptera: Braconidae) for biological control of banana skipper, *Erionota thrax* (L.) (Lepidoptera: Hesperiidae), in Papua New Guinea. Micronesica, Supplement 4, 99–105.

Sands, D.P.A., Sands, M.C. and Arura, M. 1991. Banana skipper, *Erionota thrax* (L.) (Lepidoptera: Hesperiidae), in Papua New Guinea: a new pest in the South Pacific Region. Micronesica, Supplement 3, 93–98.

Turner, D.W. 1970, Bunch covers, leaf number and yield of bananas. Australian Journal of Experimental Agriculture and Animal Husbandry, 10, 802–805.

Waterhouse, D.F. 1991, Biological control: mutual advantages of interaction between Australian and the Oceanic Pacific. Micronesica, Supplement 3, 83–92.

— and Norris, K.R. 1989, Biological control: Pacific prospects—Supplement 1. Canberra, ACIAR, 123p.