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Non-*Apis* bees as crop pollinators*

Ken W. RICHARDS
Agriculture Canada Research Station,
Lethbridge, Alberta T1J 4B1, Canada.

Non-*Apis* bees as crop pollinators. – The agronomic and economic value of bee effected pollination is discussed in terms of world food production, our diet and the well-being of society. Improved agronomic practice has increased food supply over the past 50 years, but has caused a depopulation in both numbers and species of native bee pollinator within agricultural environments. This negative impact has resulted from land clearing, cultivation, irrigation, pesticides, overgrazing, and large tract of monocultures. Populations of honey bees available for crop pollination are also decreasing. As a result, we need to develop management systems for non-*Apis* species. The overall direction of these studies has been to provide options to seed growers or horticulturists and beekeepers in their choice of pollinator for several crops. In Europe, preservation and management of habitat has been proposed as the principal method to maintain pollinator numbers with some effort directed toward developing management systems for native bee species including bumble bees, *Bombus* spp., for specific crops. In North America, efforts have focused on the development of non-*Apis* species with significant success for the alkali bee, *Nomia melanderi*, various mason bees, *Osmia* spp., and the alfalfa leafcutter bee, *Megachile rotundata*. Three of these non-*Apis* species are briefly discussed in terms of biology and management system. For the alfalfa leafcutter bee, the detailed studies necessary to successfully integrate a native bee into a sustainable agricultural system are outlined.

Key-words: Non-*Apis* bees - *Nomia* - *Osmia* - *Megachile* - *Crop pollinators*.

INTRODUCTION

Worldwide, more than 3000 plant species have been used as food. Only 300 of these are now widely grown, and just 12 species furnish nearly 90% of the world's food. These 12 include rice, wheat, corn, sorghum, millet, rye, barley, potatoes, sweet

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potatoes, cassavas, bananas, and coconuts (THURSTON, 1969). These crops are either wind-pollinated or self-pollinated. Superficially, it appears that insect pollination has little effect on the world's food supply-possibly no more than 1% (McGREGOR, 1976). However, when total animal and plant products are considered, it appears that perhaps one-third of our total diet is dependent, directly or indirectly, on insect-pollinated plants.

The importance of insect pollinators can be put in perspective by examining the total Canadian food production scene as an example. In 1991, about 68 million ha of land were cultivated. About 45 million ha were devoted to wind- or self-pollinated crops such as grains or rangeland. About 3 million ha were devoted to self-pollinated crops such as rapeseed, flax, beans, peas, soybeans, and peanuts that may receive some benefit from insect pollination. A small improvement in yield or grade can have a large positive impact on profit. The remaining 9 million ha were devoted to fruits, vegetables, and legume crops and are completely dependent on, or produced from, insect-pollinated seed. About 11 million ha were summerfallowed. Animal food products such as beef, pork, poultry, lamb, milk, and cheese contribute about half of the North American diet. These products are derived in part from insect-pollinated legumes such as alfalfa, clover, or trefoil. Insects also have a major impact on oilseed crops. More than half of the world's diet of vegetable fats and oils comes from rapeseed, sunflower, peanuts, cotton, and coconuts. Many of these plants depend on or benefit from insect pollination.

The agronomic and economic value of bee-effected pollination has been an internationally contentious issue since at least the turn of the century. Attempts to value the pollination activity of bees have ranged from "guesstimates" of no empirical substance, to informed estimates (largely by apiculturists) to a few concerted efforts by economists (see GILL, 1991). Estimates by US researchers of the value of pollination to US agriculture have ranged from US \$1.6 billion to US \$40 billion (MARTIN, 1975; LEVIN, 1983; ROBINSON *et al.*, 1989; SOUTHWICK & SOUTHWICK, 1992). Others have estimated Australia's benefits at A\$156 million (GILL, 1991) and for Canada C\$1.2 billion (WINSTON & SCOTT, 1984). The major insect-pollinated crops in the European Community were calculated to have a total annual market value of 65000 million ecus, to which pollination by insects contributes 5000 million ecus, and that by domesticated honey bees 4250 million ecus (BORNECK & MERLE, 1989). The estimates are used to justify continued public financing of honey price support schemes, increase public funding of bee related research and extension programs, enhance the efficiency of the policy making process, and to recognize the contribution beekeepers make to the well-being of society. The estimates are derived primarily for honey bee pollinated crops. Honey bees have often been credited with pollination services that are actually performed by other bee species (PARKER *et al.*, 1987). There are few estimates of the value of non-Apis pollination, and these insects are generally not appreciated. The benefits we derive from native pollinators are believed to be increasing as the honey bee industry experiences continued difficulties from mites, Africanized bees and diseases, and as crops that are better pollinated by bees other than honey bees are grown more intensively.

Recent technological advances in agronomic practices have focused primarily on improving yield, increasing the number of crops grown, and increasing the area of harvestable crops. These advances have been applied indiscriminately to the majority of crop species and have transformed farms to intensive monoculture systems. The positive results of these practices are impressive: the quality and quantity of food have increased; food costs have decreased; numerous fresh fruits and vegetables of high quality are available for much longer periods; the quality and types of prepared food products have greatly improved; and, the large labour force once required has been reduced at the same time as crop areas have increased.

Accompanying the technical advances and intensive farming practices, a negative impact on crop pollination and non-*Apis* populations evolved. For example, clearing land of trees and increased cultivation have inadvertently eliminated many of the nesting areas previously used by non-Apis pollinators. Frequent applications of broad spectrum pesticides have been responsible for the rapid decline of pollinator numbers within agricultural areas. Planting cross-pollinated crop species (ie. alfalfa in Canada, almond, apple, melons, and blueberry in the USA) in large tracts of unbroken land in disjunct areas has artificially created shortages of pollinators available for these crops. Changing irrigation practices have had negative long-term effects on soil-nesting pollinators. And, overgrazing of rangeland and the use of herbicides has indirectly reduced the presence of pollinators by decreasing diversity of pollen-nectar resources and by eliminating required plant resources that are utilized by various pollinator species in nest construction. One of the consequences of an increased food supply for the world has been a depopulation of both numbers and species of native pollinators within agricultural environments. This situation must be addressed if our agricultural ecosystems are to be sustainable.

Honey bees can no longer be relied on to consistently pollinate all crops. The North American honey bee industry continues to experience pressure from tracheal, Varroa and other mite infestations; the rapid expansion of Africanized honey bees in the New World; contamination from several diseases so that the number of colonies available for pollination is becoming alarmingly low; and the withdrawal by government (US) of the honey price support program. Thus, the honey bee industry may not be able to adequately meet the pollination needs of intensive farming, increased area of crops requiring pollination, and of developing greenhouse crops. International concerns are also being expressed that honey bees may not benefit the native biota. They have been shown to displace native pollinators from flowers, may not trigger the pollination mechanisms of the flowers they visit, may force native bees to switch to less profitable resources when they are abundant at the richest patches of flowers, and instill aggressive interactions with native *Apis* species (see Paton, 1993). These problems will have long-term, negative consequences resulting in shortages of honey and native bee populations reserved for crop pollination. The continued evaluation and development of management practices for non-Apis pollinators will help ensure adequate pollination for a diversity of crops.

Several reviews summarize the above problems (FREE, 1982; PARKER *et al.*, 1987; ROBINSON *et al.*, 1989; SOUTHWICK & SOUTHWICK, 1992; TORCHIO, 1990, 1991;

CORBET *et al.*, 1991; OSBORNE *et al.*, 1991; WILLIAMS *et al.*, 1991). Recommendations for and approaches used to increase the availability of pollinator numbers has varied. In Europe, preservation and management of habitats thought suitable for bees' forage or nesting sites have been repeatedly proposed as a method to maintain or increase pollinator numbers. Enhancing native pollinator populations by habitat management is a potentially cost-effective option that deserves attention, and may become essential if honey bees become less readily available (CORBET *et al.*, 1991). Habitat management will be most effective if planned on a scale larger than that of an individual farm, and it therefore requires coordination on a regional scale across government levels. For the few crops and many native flowering plant species unsuited to pollination by managed colonies of bees, this is the only viable option. There has been some development in Europe of non-*Apis* species as managed pollinators (TASEI, 1975, 1977; KRUNIC & BRAJKOVIC, 1991; HEEMERT *et al.*, 1990). In North America, efforts have focused on the development of non-Apis species as managed pollinators for specific crops with significant success for the alkali bee, *Nomia melanderi* Ckll., various mason bees, *Osmia* spp. and especially for the alfalfa leafcutter bee, *Megachile rotundata* F. There have been proposals for habitat management programs, but little positive action, especially in intensive agricultural systems. ROBINSON *et al.* (1989) suggested that additional research resources for honey bees would satisfy all future crop pollination requirements. Throughout the world, a few other successful programs exist which enhance native pollinator numbers, (i.e., mason bees for apple pollination in Japan, MAETA, 1978).

The remaining part of this paper summarizes successful commercial management systems for four non-Apis pollinators: the alkali bee, mason bees, bumble bees, and the alfalfa leafcutter bee.

ALKALI BEE, *Nomia melanderi*

The alkali bee is endemic to certain arid and semi-arid portions of the western United States. It was a valuable native pollinator of alfalfa, onion, sweet clover, and mint, especially during the 1960's and 1970's (JOHANSEN *et al.*, 1982). It has decreased in importance recently because of the increased use of the alfalfa leafcutter bee for these crops. It is a solitary, gregarious bee that usually nests in large aggregations of about one million nests per acre in alkali flats with a continuous source of subsurface moisture, and in saline soils with a silt loam to fine sandy loam texture.

Adults emerge in early summer and females construct nests and collect pollen for their young over a period of about 30 days. Usually only one nest is prepared and provisioned per female. Nests vary little in their architecture with each having a main burrow leading from the entrance hole to a carved out chamber 12-60 cm below the soil surface. On average, each female has 15 to 20 progeny in well-managed or artificial beds, depending on the type of nesting site. Daily flight periods normally begin 2-3 hours after sunrise and end by 4-5 pm during mid-summer periods. They can visit and trip up to 12 alfalfa florets per minute. The alkali bee, unlike other alfalfa pollinators, flies through the canopy of the crop as it visits flowers and thereby increases its pollination efficiency on that crop.

Often, after a natural nesting site has maintained a large bee population for a few years, it becomes unsuitable and the bee population rapidly declines. Decline may bedue to flooding, decreased moisture, development of a thick and hard crust on the soil surface, diseases, parasites and predators of immature stages, pesticides, trampling by livestock, traffic by vehicles, and encroachment of salt-tolerant vegetation. Management techniques have been developed to protect natural nesting sites from these hazards and to maintain the sites either by regulating the water supply, reworking the soil surface or eradicating encroaching vegetation (STEPHEN, 1960a, b; JOHANSEN *et al.*, 1982). Attempts have been made to create new sites where they are needed. The new nesting sites or bee beds must have an adequate moisture supply, be relatively free of weeds, and protected from pests. The alkali bee may migrate to thenew beds or be transported in undisturbed soil from established beds and imbedded at the new site during the winter while the bees are in the overwintering stage.

MASON BEES, *Osmia* spp.

Mason bee species from several countries are recognized as potential pollinators for diverse crops, including orchard, vegetable, greenhouse, and field crops. The osmiine bees, unlike other Megachilinae, collect mud, or mud mixed with macerated leaf material, or only macerated leaf material to construct their cells. Generally the bees are solitary yet gregarious. The following three examples of different species demonstrate the needs and evaluations required for successful commercial management. Other *Osmia* spp. (i.e., *rufa*, *ribifloris*, *coerulescens*, *sanrafaelae*, *bruneri*, *atriventris*) also have potential as crop pollinators, but considerable effort to understand their biology and to develop appropriate management systems (TASEI, 1973a, b; KRISTJANSSON, 1989; TORCHIO, 1991) is still required.

The blue orchard bee, *Osmia lignaria propingua* is distributed across the continental US and southern Canada. Studies on this species began about 20 years ago when the number of honey bee colonies in the US was declining and the area planted to orchard crops was increasing; a pollination crisis for many cross-pollinated orchard crops, specifically apple ad plum was forecast (TORCHIO, 1976). Commercial success for *O. lignaria* can be attributed to TORCHIO (1976, 1982, 1985, 1990) who found: apple pollination is maximized when 250 female bees are nesting per acre; 300 females/acre for almond; pollination by this bee continues when honey bees cease flight during inclement weather; pollination is evenly distributed across orchards when nest materials are evenly distributed throughout orchards; population sizes can be increased under intensively farmed orchard systems; exposure to insecticides is minimized because the nesting cycle can be completed during the flowering period; nesting populations can be moved; management systems have been developed for commercial-sized populations; inexpensive but successful control methods have been developed for the more important nest associates; large field-trapped populations have been obtained; and populations have been successfully transported intercontinentally.

The horned-faced bee, *Osmia cornifrons* is native to Japan where it has long been established as a commercial pollinator of apple and plum (MAETA & KITAMURA, 1965a, b, 1974). Commercial apple production in Japan has required the application of toxic materials during the flowering period. Use of pesticides, combined with clean cultural practices, were responsible for significantly reducing pollinator populations. Orchardists resorted to labour intensive hand-pollination, but this was not cost effective. Viable management systems were subsequently developed to utilize this bee as a cost-effective pollinator (MAETA, 1978). The system requires the increase of populations away from the orchards. From these, subpopulations are introduced annually back into the orchard environments. The bees moved into orchards are treated as an expendable commodity.

In Europe, *Osmia cornuta* has been evaluated as a pollinator of apple, almond and other crops (TASEI, 1973a, b; ASENSIO, 1983; TORCHIO & ASENSIO, 1985; KRUNIC & BRAJKOVIC, 1991). Its potential value can be summarized as follows: large natural populations occur in some areas of Europe, and field-trapping efforts have been successful in those areas; its biology is similar to other *Osmia* spp. and hence is amenable to management systems developed for other species; it has few nest associates; its foraging biology is similar to other species hence its effectiveness is significant; managed populations readily accept commercial nesting materials; and populations released in orchards increase.

BUMBLE BEES, *Bombus* spp.

Bumble bees have drawn the attention of biologists for more than a century. Considerable knowledge on their biology, nesting site and flower preference, colony architecture and size, and associated pests is known (SLADEN, 1912; FREE & BUTLER, 1959; ALFORD, 1975; HEINRICH, 1979). Until recently, bumble bee colonies were reared mainly for specific scientific purposes. Methods have been described to induce *Bombus* species to start and maintain colonies in captivity (PLOWRIGHT & JAY, 1966; POMEROY & PLOWRIGHT, 1980). Renewed interest in year-round rearing of bumble bees for high-value crops (i.e., tomato, cucumber) in greenhouse industries in Europe and kiwi fruit in New Zealand has resulted in refinements of techniques (ROSELER, 1985; HEEMERT *et al.*, 1990; EIJNDE *et al.*, 1991) making the efforts economically viable. Savings in labour costs and reliability of the bee are the principle reasons for success. Other successes in using bumble bees for greenhouse crops are now being reported (BANDA & PAXTON, 1991; KEVAN *et al.*, 1991; STRAVER & PLOWRIGHT, 1991). Bumble bee rearing has been commercialized and some companies specialize in providing colonies at specific stages of colony development. With the refinements in rearing techniques, there is potential now to place bumble bees on field crops, although the economic viability needs to be determined.

ALFALFA LEAFCUTTER BEE, *Megachile rotundata*

Historical perspective: The alfalfa leafcutter bee is the most important pollinator of alfalfa in Canada and the Pacific Northwest of the USA and is increasing in importance throughout the world. Flowers of alfalfa must be cross-pollinated to produce seed. Alfalfa seed production in western Canada has been highly variable over the past 50 years, ranging from a high of 9.7 million kg, in 1948 (12.7 M kg in 1989) to a low of 450 thousand kg in 1969. During the 1940's, southern Alberta was Canada's main alfalfa seed production area, but this shifted during the 1950's to the parkland areas of the prairie provinces. Eventually production in both areas greatly decreased because increased irrigation, cultivation, land clearing, or pesticide use destroyed the nesting sites or populations of native pollinators. Honey bees are of negligible value for alfalfa pollination because only 0.8% or less of the flowers visited are pollinated (HOBBS & LILLY, 1955). By 1950, Canada was importing alfalfa seed to meet domestic needs rather than exporting excess production. However, this situation has now reversed. In 1988, 1.1 million kg of seed were exported from western Canada; this was the largest amount in 30 years. Increases in growing area of 40 to 60% in recent years reflect the rapid growth of the industry (RICHARDS, 1987a). In 1976, 1625 ha were in pedigree seed production and by 1992, this had increased to 25100 ha plus about 3000 ha of common seed. Expansion of the industry can be attributed to the alfalfa leafcutter bee and to the good demand for hardy, adapted, Canadian-bred cultivars, low production costs and good economic returns for both bees and seed in comparison with competitive cash crops. During the last few years, seed yields on irrigated land in southern Alberta have averaged 350 kg/ha and the yearly production of bees has almost doubled. Experienced managers sometimes produce yields of up to 1100 kg/ha. Without leafcutter bees, only 50 kg/ha of seed would be produced.

Management objectives: The first leafcutter bees were imported into Canada in 1961. Since then, improved management practices have resulted in the steady expansion of the alfalfa seed and leafcutter bee industries. Large numbers of bees are needed to pollinate the crop. For this reason, the loose-cell system of bee management was developed (HOBBS, 1964, 1973; RICHARDS, 1984a, 1987a). This system places the optimum number of bees on the crop at the appropriate time to obtain a high seed set and an adequate return of viable bees for the following year (RICHARDS, 1982). This system enables easy removal of bee cells from laminated grooved nesting materials for storage over the winter, without destroying the nesting material. The system enables control of parasites, predators, and diseases through various management procedures, including hive construction, incubation, and removal and tumbling of cells from the hives. It also makes efficient use of cold storage and incubation facilities to synchronize bee emergence with the beginning of flower bloom. Beekeepers can take samples of cells from their current production to accurately estimate numbers of intact cocoons, females, parasites, and diseases (HOBBS & RICHARDS, 1977; RICHARDS & KOZUB, 1979). Therefore, improvements in beekeeping practices can be monitored and guidelines provided when bees are bought, sold, exported, and rented by alfalfa-seed growers. Although the loose-cell system of bee management requires substantial initial financial investment in specialized equipment and demands intensive and proper handling of bees, careful managers realize profits from the sale of excess bees.

Various levels of leafcutter bee management exist (BOHART, 1972; RICHARDS, 1982). The higher levels of management tend to require more skill, knowledge, and capital, and incorporate more sophisticated equipment than the lower levels. Of course those managers operating at higher levels of management have reduced much of the risk and uncertainty they face, have allocated resources through management decisions which have allowed a greater flexibility of choice, and hence, have an increased chance that expectations will be consistently fulfilled.

The alfalfa leafcutter bee is of Eurasian origin. It is solitary and gregarious. At the hive, the female constructs about 30 cells in a life time. The cells are built of leaf pieces and provisioned with pollen and nectar. One egg is laid in each cell. The larvae pass through 4 instars (WHITFIELD *et al.*, 1987) and a base temperature of 15 C and 166 degree-days are required to complete immature stage development (WHITFIELD & RICHARDS, 1992). One generation per year is normal in Canada, but up to three generations per year are possible in southern California (BITNER, 1992). The normal sex ratio is near 2:1 M:F.

Bloom synchrony: The usefulness of this bee begins when alfalfa starts to bloom and ends when no flowers remain to be pollinated or when tripped flowers do not have time to set mature seed before harvest. The optimum relationship of bee population and flower density to time can be described as curvilinear. The relationship can only be achieved by synchronizing bee emergence with the commencement of flower bloom. Techniques to synchronize the bees with the bloom have been easier to develop than techniques to control the bloom of the crop. The development and emergence of bees can be regulated more easily by using controlled incubation facilities than by relying on field conditions (RICHARDS, 1984a; STEPHEN, 1981). Various incubator designs are used for different purposes (RICHARDS, 1982).

In general, cells containing prepupae are removed from hives at the end of the season and stored at low temperatures for several months to retard development and synchronize emergence. Early the following June, cells are placed in high temperature incubators (about 30 C) for about 3 weeks to synchronize adult emergence with the beginning of alfalfa bloom. Development and emergence of bees can be regulated easily by modification of incubation temperature and can be delayed for several days with no mortality (RANK & GEORZEN, 1982; UNDURRAGA & STEPHEN, 1980). Temperatures in incubators should be lowered when inclement weather (cold, rain, wind) reduces the chance of successful field release of bees, when an insecticide needs to be applied to control a pest insect, when waiting for an insecticide residue to dissipate, and when, through improper incubation timing, insufficient bloom and food for the bees occur on the field (RICHARDS, 1982). Males emerge before females. Emergence is usually completed in field shelters.

A more detailed study (RICHARDS & WHITFIELD, 1988) on the survival and development of prepupae from different locations revealed no significant interaction in emergence between sex and temperature across locations for incubation temperatures from 15 to 37 C. For the intermediate range of temperatures of 25-35 C, the range commonly encountered in commercial beekeeping operations, a lack of significant interaction between temperature and location occurred. This means all bees responded to temperature similarly. Survival was high, except for high temperatures. As expected, rate of development increased with increasing temperatures up to 32 C and then decreased slightly. Base temperature was 15.7 C for development, and number of degree-days for 50% emergence was 295.

A chalcid wasp, *Pteromalus venustus*, the most common pest insect associated with the bee in western Canada emerges over a 4-day period starting on the 8th or 9th day of incubation. Temperature also influences its rate of postdiapause development and emergence during incubation (WHITFIELD & RICHARDS, 1985, 1987). This information is especially valuable for timing control measures for this parasitoid. Base temperature for 50% emergence is 15.0 C and DD necessary to attain 5 and 50% emergence were 151.5 and 162, respectively. Note the close similarity between the base temperature for the bee (15.7) and the main parasite (15.0). The wasp develops so rapidly at 30 C that, if it is poorly controlled during its first emergence, another emergence can occur before or just as the bees are taken to the field, resulting in further loss of bees. The influence of temperature on survival and development of non-diapausing *Pteromalus* has been determined. The most common methods of control during incubation include the use of UV light traps placed over water, and placing dichlorvos resin strips in the incubator just prior to parasite emergence.

Nesting materials: Leafcutter bee hives are used by the female to construct and provision cells and lay eggs; parasitism occurs primarily in hives. A hive requires precise construction of good-quality material to ensure high return of viable cells by providing an acceptable, parasite-free home for the bee (RICHARDS, 1978, 1984a, 1987a). Various nesting materials with optimum tunnel length and diameter have been evaluated and each have advantages and disadvantages. One of the main premises of the loose-cell system of bee management is that the cells must be easily removed from the nesting material, without destroying the material. Laminated grooved nesting material of either pine wood or polystyrene are commonly used and are adapted for easy cell removal.

Most Canadian beekeepers use automatic cell removers to ease the removal of cells from the nesting material. The cells are then passed through cylindrical tumblers to remove debris, debris-feeding insects, predators, plant foliar moulds, and chalk-brood cadavers. This sanitation practice can remove up to 17% by weight of unwanted material (RICHARDS, 1984b).

Shelters: Shelters protect the hives and nesting bees from adverse weather. The size of shelter is governed by economic use of construction materials, transportability to and from seed fields and between fields, volume of overwinter storage space, and area to be pollinated (RICHARDS, 1984a). Because they are large and easily visible, the shelters help the bees return to their hives. Some shelter designs encourage efficient use of the bees and others do not (STEPHEN, 1981; RICHARDS, 1983). Shelter designs have been evaluated for construction materials, heat build-up, light intensity, wind turbulence, orientation patterns, effect on foraging activity of the bee, bee quality and reproduction, and dropping of leaf pieces used in cell construction. Shelters are faced easterly and evenly spaced through the crop with one shelter per 1.2 ha. In general, bees tend to pollinate alfalfa about twice as far to the east as to the west of the shelter; therefore, shelters are generally placed closer to the western edge of the crop than the eastern edge. Seed yields are usually highest immediately in front of shelters and decrease with distance from the shelter (RICHARDSS, 1983, TASEI & DELAUDE, 1984). The amount of seed yield decrease varies by year and is related to total flying hours.

Population recommendations: When the bee was first imported into Canada only 500 female bees/ha were recommended (HOBBS, 1964). The large population required for pollination did not exist, but as the number of bees increased, the recommended rate also increased (20000 bees/ha Hobbs, 1967; 50000 bees/ha HOBBS, 1973; RICHARDS, 1984a). In some years 50000 bees/ha appears sufficient to provide a near uniform seed set across a field, but in many years it is not enough. Therefore, a theoretical approach was developed to predict the probability of an individual flower being pollinated under various pollinator and flower densities. These estimates are a necessary prerequisite to recommending the numbers of pollinators needed per unit area of crop for maximum pollination. The pollination model has been used to compare pollinator species, leafcutter, honey, and bumble bees for cicer milkvetch and sainfoin (RICHARDS, 1987b; RICHARDS & EDWARDS, 1988). Providing realistic recommendations to producers on the optimum number of pollinators (for any non-*Apis* pollinator) required for a crop is one of the most important and basic pieces of knowledge that we should be generating. Because of the complexity of integrating the bee, bee-crop interaction, and other related components, it is also one of the most complex and difficult.

Winter storage: Leafcutter bee hives are removed from the field during August and bee cells are removed from the hives during September through December. Cells containing prepupae are normally stored at 0-10 C for 7-10 months to reduce losses by parasites and predators, to protect them from excessively cold temperatures, and to arrest prepupal development until the spring or when adult bees are needed (RICHARDS *et al.*, 1987). Duration and temperature of cold storage and subsequent temperature of incubation are important factors that influence the emergence of adult leafcutter bees.

Pests and diseases: The loose-cell system of bee management facilitates control of natural parasites and predators that prey on the bees or feed on stored products. The system has been criticized because the types of hives, the laminated grooved nesting materials, and the incubation of loose cells in trays, were thought to be conducive to an increase of harmful pests. These criticisms are unfounded. Over the last 30 years the bee has been in Canada, mortality attributable to the 21 species of parasites or predators associated with the bee has accounted for about 1% of the total bee population. Under the intensive loose-cell system, parasites and predators can be controlled by precise construction of hives (HOBBS, 1973; RICHARDS, 1983a), controlled incubation and light traps, immersion of cells in insecticides (not practised) (BRINDLEY, 1976; PARKER, 1979), placement of dichlorvos strips in incubators (HILL *et al.*, 1984) and fall storage areas, and physical separation during the removal and subsequent tumbling of cells from the hives (RICHARDS, 1984a). Many of the techniques have been directed at reducing the population of emerging adult parasites and preventing parasitism during incubation. This has required accurate prediction of the emergence of parasites during incubation and the scheduling of appropriate control measures.

Some viral, bacterial, and fungal diseases of leafcutter bees are known (HACKETT, 1980; INGLIS *et al.*, 1992). Chalkbrood disease, caused by *Ascosphaera* *aggregata*, is the most serious and was first found in Canada in 1982 (RICHARDS, 1985). In Canada, the disease is found mainly in southern Alberta, where levels (less than 3%) have not reached those in parts of the US (up to 60%) (STEPHEN *et al.*, 1981). Mode of dispersal, infestation of bee larvae, sporulation, and associated symptoms caused by this pathogen have been described (MCMANUS & YOUSEFF, 1984; VANDENBERG *et al.*, 1980, 1982). Effective control measures have been sought (STEPHEN *et al.*, 1982) with trhe most promising being the fumigant paraformaldehyde (GOERZEN & WATTS, 1991).

Productivity indicators: Reliable productivity indicators are required by beekeepers to improve their operations, to assist them in evaluating management decisions, and to warn of new problems (pest or diseases). They are needed when the bees become items of commerce so that sellers obtain fair prices and their customers obtain fair value (HOBBS & RICHARDS, 1977; RICHARDS & KOZUB, 1979). Methods to provide statistically accurate estimates using x-radiography have been developed and incorporated into an industry-run quality control laboratory. Samples submitted by beekeepers since 1970 indicate a gradual improvement in the quality of bees produced. Productivity has increased while the percentage of incomplete (dead) cells has decreased. The productivity indicators for the incubation test show that about 33%+ of the incubated cocoons contained females. These estimates indicate that beekeepers are incorporating new and recommended procedures into their operations.

The loose-cells system has made Canadian leafcutter beekeepers the world's leading suppliers of quality cells. In the past few years, 150-300 million surplus bees have been exported annually, mainly to the US, but also to Argentina, countries formerly part of the USSR, and several European countries.

Pollination of other crops: The usefulness of the bee for legume forage crops other than alfalfa, and on field and horticultural crops for seed or fruit production has been assessed only in a few commercial fields and experimental plots. The bee's potential to pollinate legume forage crops in western Canada was investigated through mass-screening of 30 plant species (RICHARDS, 1991). Most perennial and biennial legumes currently grown in Canada require cross pollination and had favourable seed sets and yields when exposed to leafcutter bees. Most annual legumes did not benefit from leafcutter bees. The intent of these studies was to provide an option to seed growers in their choice of pollinator for these crops. We have begun detailed studies comparing pollinator species for some of the more promising crops. The theoretical model presented earlier was used to predict the bee population required to pollinate varying flower densities. The effectiveness or seed-setting ability of the various pollinators determines the choice of pollinator and management recommendations. When recommendations are being developed, it is important to determine whether or not the crop can support the recommended pollinator. This is especially important for non-Apis bees because of their short flight ranges. Estimates of potential leafcutter bee productivity for most crops are still required. These estimates are expected to vary within a country and by country.

Future concerns: The alfalfa leafcutter bee industry in western Canada and North America has become well established through the organization and promotion of alfalfa seed grower associations. Many of the management techniques developed to date are directed towards controlling or modifying particular problems. Parasites and predators have made the development of specific control practices necessary. Application of pesticides is another major problem where the impact of interactions needs further research. With increased emphasis on sustainable agriculture and integrated pest management, losses to pesticides should become minimal. Bee diseases, including chalkbrood, are poorly known and new and modified equipment will be needed for effective control. Solutions to these management problems are important and in most cases achievable. Risk reduction is possible. Leafcutter bees could be used in combination with honey bees in California to improve alfalfa pollination. The usefulness of the alfalfa leafcutter bee as a pollinator of diverse forage legume crops and other crops for seed production needs to be thoroughly investigated.

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