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Provisioning services from ants: food and pharmaceuticals

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ABSTRACT. The present review assesses the role of ants in providing ecosystem provisioning services in the form of products such as food and medicine. Many species of ants constitute an inexpensive, protein- and mineral-rich, unconventional human food source. Some ant species are also utilised in traditional entomotherapy by indigenous people, or as a complementary and/or alternative medicine, in many parts of the world. Recent biochemical and pharmacological investigations are increasingly providing evidence regarding the medicinal significance of ant species. The well-developed immune system and anti-microbial chemicals that evolved in ants for defence against pathogens can be exploited for the treatment of human diseases. This important taxon may have enormous potential for providing future benefits to mankind as a source of pharmaceuticals and as rapidly and conveniently farmed minilivestock, for an increasing human population.

Keywords: Ecosystem services, human entomophagy, edible ants, entomotherapy, ant-derived medicines

INTRODUCTION

Ecosystem transformations in the last century, due to agricultural intensification and rapid industrial and urban development, have imposed pressures on biological diversity (Wilson 1988; Palmer *et al.* 2004). Therefore, there is an urgent need to create interest and awareness regarding functional biodiversity (Rastogi & Kumar 2009), biodiversity conservation (Novacek 2008) and also the economic services and resources provided by biodiversity. The median world population estimate by the year 2050 is over nine billion (United Nations 2008). Achieving sustainable food production for this rapidly increasing population without further accelerating the decline of biodiversity will be a major global challenge (Hails 2002; Miller 2008). Human entomophagy (consumption of insects by human beings), already a practice of indigenous tribal populations worldwide, therefore needs to be encouraged (Yen 2009a,b). Being herbivores, predators, scavengers or omnivores, insects not only occupy a variety of trophic levels but also exhibit high food conversion efficiencies and energetic values; in one Mexican study, insects raised on organic wastes provided 288–575 kcal/100g (Ramos-Elorduy 2008**)**. There is therefore a need to document information about key insect taxa and the range of resources provided by them.

Ecosystem services are the benefits people obtain from ecosystems, including provisioning, supporting, regulating and cultural services (Daily *et al.* 1997; Millennium Ecosystem Assessment 2005). Ecosystem services are vital in contributing to the functioning of the earth's life-support systems and in human welfare (Costanza *et al.* 1997). They are under threat due to global environmental changes resulting from anthropogenic activities (Steffen *et al.* 2004; Schröter *et al.* 2005). Human consumption of animal body parts and products, and zootherapy (healing of humans using animal-derived products), have been practised since ancient times (Costa-Neto 1999; Lev 2003; Alves *et al.* 2008; Mahawar & Jaroli 2008). Insects constitute an excellent source of protein (Gullan & Cranston 2000) and have probably been used as food for millennia (Morris, 2008). While use of honey and wax from honey bees is well known, utilisation of ants as food and medicine has received less attention (DeFoliart 1989; Yhoung-aree *et al.* 1997; Costa-Neto 2002). But ants, being locally abundant, are documented as significant food sources for a range of non-human primates (e.g., Di Fiore *et al.* 2005; Isbell & Young 2007; Sanz *et al.* 2009). Similarly, the colonial organisation and easy availability of ants have probably contributed to their exploitation by indigenous populations in obtaining ecosystem goods in the form of food (Roy & Rao 1957; Sribandit *et al.* 2008) and medicine (Chen & Alue 1994; Oudhia 2002) as well as the services of predatory species in insect pest management (Huang & Yang 1987) in many countries. Ancient European literature mentions the use of ant extracts for treatment of sore eyes, weak vision and cataracts, while in many parts of Central Asia, ants have been used in the treatment of arthritis (Lockhart 2000 and references therein). As per the Millennium Ecosystem Assessment conceptual framework, food and drugs constitute provisioning services provided by ants, while soil modification is a supporting service, and the processes of pollination, seed dispersal and herbivore suppression are regulating services. Since ants have provided artistic, religious and spiritual services to tribal peoples (Cherry 1991; Ramos-Elorduy 2009), and have more recently been utilised by scientists for scientific services (e.g., Andersen 1997), they also provide cultural services to mankind (Fig. 1).

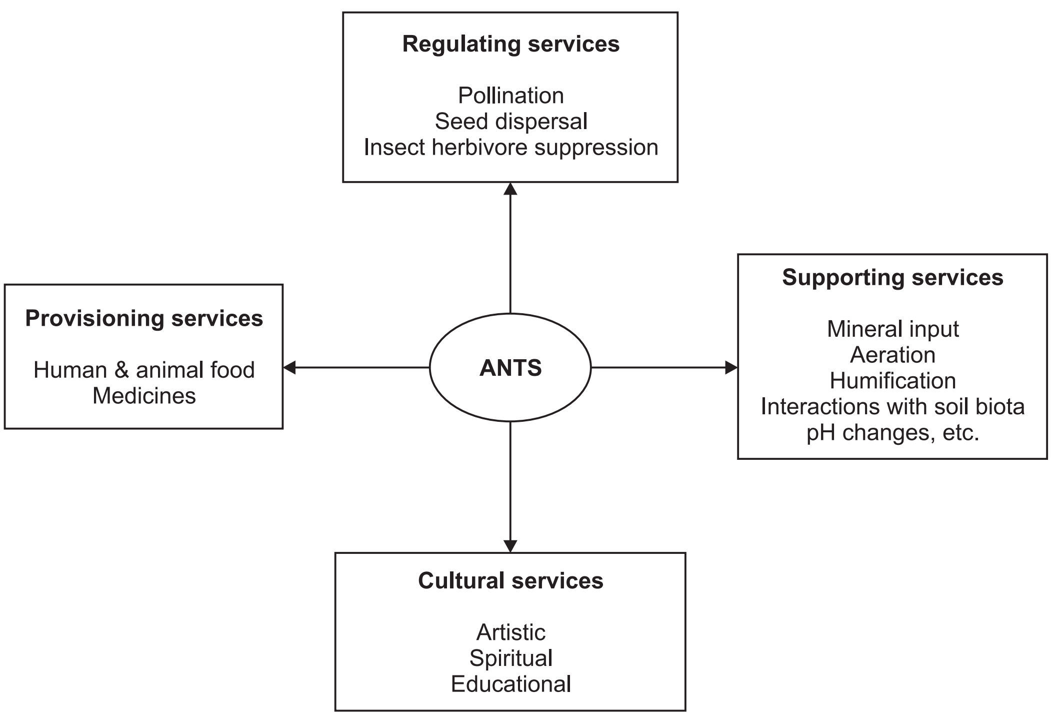

Fig. 1. Ecosystem services (in the form of provisioning, regulating, supporting and cultural services) processes and economic resources provided by ants.

Ants have direct economic values which include consumptive use value (since they are locally consumed goods) and productive use value (since ant products are sold in markets) as well as indirect economic value (through their impact on ecosystem processes and services) (Primack 2000). While several ant species are harvested for food, a considerable number are utilised as complementary alternative medicines.

In the present review, I attempt to discuss and synthesize the existing information on the benefits derived from ants by their direct utilisation as food and in the treatment of human diseases. I indicate the future scope for exploiting basic information on immune systems and disease resistance ability of ants, to access pharmaceuticals of benefit to mankind. I also draw attention to some future research directions to obtain nutritive and medicinal benefits from ants. Taking into consideration the vast amount of research done on the supporting and regulating services of ants, these aspects will be dealt with in a separate review.

HUMAN UTILISATION OF INSECTS AS FOOD AND MEDICINE

Entomophagy and entomotherapy (medicinal uses of insects) are common among the indigenous, tribal people of many countries (Sutton 1988; DeFoliart 1989, 1995; Costa-Neto 2005; Lawal & Banjo 2007). Indeed, edible insects constitute an integral part of the traditional food systems in several Asian countries including India (Das 1945; Rajan 1987; Kato & Gopi 2009; Kumari & Kumar 2009; Srivastava *et al*. 2009), Nepal (Burgett 1990), Thailand (Yhoung-Aree & Viwatpanich 2005), China (Chen & Alue 1994) and Japan (Pemberton & Yamasaki 1995). Australian aborigines (McKeown 1944; Cherry 1991; Conway 1994), hunter-gatherers of Africa (Chavunduka 1975; Dreyer & Weameyer 1982; Banjo *et al.* 2003; Christensen *et al.* 2006; Morris 2008), and subsistence farmers of Mexico (Ramos-Elorduy *et al.* 1997a, b) and Brazil (Costa-Neto 2002; Alves 2009) also use insects as part of their regular diet. Consumption of insects was probably prevalent in European countries too, since the importance of insects as human food was mentioned by Herodotus, Aristotle and Pliny (Bodenheimer 1951).

Edible insects constitute a good source not only of protein, fats, carbohydrates and vitamins (Ramos-Elorduy *et al.* 1997), but also of essential minerals such as calcium, zinc and iron (DeFoliart 1992; Banjo *et al.* 2006). They are sometimes referred to as mini-livestock (DeFoliart 1995). Since many insects such as beetles, grasshoppers, locusts, ants, termites and lepidopteran larvae utilised as food are also pests, consuming them has additional advantages (Nongo 2005).

Human entomophagy has contributed significantly to the reduction in protein deficiencies in countries such as Nigeria (Fasoranti & Ajiboye 1993). Mass production of insects could therefore help in preventing malnutrition (Robert 1989).

Further, traditional insect-derived medicines are used in many parts of the world including India (Wilsanand *et al.* 2007; Padmanabhan & Sujana 2008), China (Liu 1991; Luo 1997), Japan (Mitsuhashi 1997), Korea (Pemberton 1999), Australia (Crozier *et al.* 2010 and references therein), Africa (Van Huis 2002), Mexico (Ramos-Elorduy 2006) and Brazil (Costa-Neto 2002; Alves 2009 and references therein).

ANTS AS FOOD

Distribution of ant entomophagy

Many species of ants constitute a cheap, unconventional but significant renewable protein source in human nutrition (DeFoliart 1989; Yhoung-Aree *et al.* 1997). Many families supplement their family income by harvesting and selling ant species in Thailand, Laos, Myanmar and Vietnam (Yhoung-Aree & Viwatpanich 2005; Sribandit *et al.* 2008), Indonesia (Césard 2004) and Chhattisgarh in India (Oudhia 2002). All stages including eggs, larvae, pupae and adults, particularly the reproductives, are utilised as food, although the particular stage used varies with species.

An amazing variety of ant species are used as food by tribal peoples in many countries including India, Indonesia, Thailand, China, South and Central America, Australia and Africa (Long 1901; Skaife 1979; DeFoliart 1989, 2002; Césard 2004; Decaëns *et al.* 2006; Yen 2009b) (Table 1). In ancient China, edible ants constituted delicacies for the royalty (Chen & Alue 1994).

Table 1: Ant species utilised as food in various countries

Ant species (stage(s) utilised as food)	Country	References
Oecophylla smaragdina (Fabr.) (all stages)	Africa Australia India	Nkouka (1987) DeFoliart (2002) and references therein Veeresh (1999); Oudhia (2002); Srivastava *et al.* (2009)
	Thailand, Laos PDR, Myanmar	Yhoung-Aree & Viwatpanich (2005); Sribandit *et al.* (2008); Offenberg & Wiwatwitaya (2009, 2010)
(larvae and pupae)	Philippines	Starr (1991); Gullan & Cranston (2000)
Crematogaster sp. (brood)	Thailand China	DeFoliart (2002) and references therein J.R. Fellowes, pers. comm.
Polyrhachis dives F. Smith *(=vicina* Roger) (all stages)	China	Chen & Alue (1994)
Pogonomyrmex barbatus (F. Smith) *Atta cephalotes* (Linn.), *Atta sexdens* (Linn.), *Atta laevigata* (F. Smith), *Atta mexicana* (F. Smith) (alate females, soldiers) *Liometopum apiculatum* Mayr and *Liometopum luctuosum* Wheeler („Escamoles“) (larvae and pupae) *Myrmecocystus melliger* Forel, *Myrmecocystus mexicanus* Wesmael (adults "repletes")	Latin America	Ramos-Elorduy & Pino (1989); Ladrón de Guevara *et al.* (1995); Ramos-Elorduy *et al.* (1997); Ramos-Elorduy (2006)
Camponotus inflatus Lubbock (adults) *Camponotus cowlei* Froggatt (adults) *Melophorus bagoti* Lubbock (adults)	Australia	Bodenheimer (1951); Conway (1994) DeFoliart (2002) and references therein
Camponotus brutus Forel (NA) *Carebara vidua* F. Smith (reproductives) *Camponotus* spp. (adults)	Africa	Nkouka (1987) Nonaka (1996)

Note: NA—Information not available

The indigenous Li people of Hainan Island, south China, still eat the brood of *Crematogaster* sp. (John Fellowes, pers. comm.). *Polyrhachis dives* F. Smith (often referred to in China by the synonym *P. vicina* Roger) constitutes one of the most important insect foods in China and is consumed in dried or powder form, and also as wine (Luo 1997). The consumption of such ant species in China is predominantly based on belief in their beneficial medicinal effects.

Many species of ants, and particularly *Oecophylla smaragdina* (Fabr.), are consumed by aborigines in many parts of Australia and Papua New Guinea (Meyer-Rochow 1973; DeFoliart 2002 and references therein). In northern Australia, larvae and pupae of *O. smaragdina* are made into balls and eaten. In many parts of Australia such as northern Queensland, the eggs, larvae and adult ants are mashed up in water by the natives to prepare a pleasant sour drink. Honey-pot ants, which are mentioned in aboriginal mythology, include the black honey-ant *Camponotus inflatus* Lubbock, the golden-yellow honey-ant *Camponotus cowlei* Froggatt and the red honey-ant *Melophorus bagoti* Lubbock, and are a favourite food of aboriginal societies, particularly in arid parts of central Australia (Conway 1994; Yen 2005). They are either eaten at the digging site itself by biting off the gaster, or mixed with ground flour to make a sweet dough. The largest repletes, with gasters as large as marbles when filled with honey, occur in *C. inflatus*. Aborigines in northwestern South Australia greatly relish these ants which they collect by digging large pits after locating the nest entrance.

In some parts of India, tribal people eat *O. smaragdina,* either in raw form as chutney, or cooked (Long 1901; Srivastava *et al.* 2009). In the Kanara region of South India, parts of Nagaland, Chhattisgarh in Madhya Pradesh and in parts of Orissa in India, mashed up workers of *O. smaragdina* are used as food by various tribes (Veeresh 1999 and references therein; Oudhia 2002; Srivastava *et al.* 2009). The Muria tribals of Chhattisgarh in India roast these ants in the leaf nests and prepare a sauce, or sun-dry and powder them for later consumption (Roy & Rao 1957).

Larvae of *Crematogaster* sp. and all stages of *O. smaragdina* are used as food in Thailand and Laos (DeFoliart 2002 and references therein). The larvae, pupae and even adults of *O. smaragdina* are used to give a sour taste to food. The eggs and larvae are eaten either raw as spicy salads (Raksakantong *et al.* 2009) or cooked as part of soup (Vara-asavapati *et al.* 1975). In Thailand and Philippines, the brood (larvae and pupae) of *O. smaragdina* are harvested and sold in the market (Offenberg & Wiwatwitaya 2009, 2010).

Toasted gravid females of the leaf-cutting, fungus-growing ants of *Atta* spp. are highly relished delicacies in South and Central America, particularly in Colombia, Brazil and Argentina (Wallace 1853; Bodenheimer 1951; DeFoliart 2002, 2003). Swarming females (locally known as “culonas” in Colombia) of *A. cephalotes* (Linn.) and *A. sexdens* (Linn.) are caught and collected during nuptial flights, and their gasters consumed (DeFoliart 2002; Decaëns *et al.* 2006). Collection and selling of *Atta* spp. during the 3-month season can fetch money equivalent to that earned in a whole year by a rural worker (DeFoliart 2003). Amerindian groups living in the Amazon basin are recorded to use leaf- and litter-consuming invertebrates, including the large leaf-cutting ants, as protein sources (Paoletti *et al.* 2000). This enables them to take advantage of such highly renewable sources of animal protein, particularly during difficult periods of food availability including the rainy season when fish and game are scarce. Moreover, the success rate of locating ants is estimated to be close to 100 percent on account of easily available knowledge about the location of ant colonies and the gregarious aggregations. Ant larvae, workers and the egg-loaded queens of many ant species are used directly as food or in the treatment of a variety of diseases (Table 1 & 2). This may be because alate ants have a higher percentage of fat than workers (Redford & Dorea 2009). Biomass of *Atta* spp. captured annually in some parts of Mexico is estimated to be 39 tons/year/family (Ramos-Elorduy 2009). Since leafcutter ants are serious pests (Hill 1983), consumption of these ants provides a double benefit.

Ants belonging to the genus *Liometopum* (the “escamole” ants) are regarded as delicacies and are enjoyed by all social classes, even constituting expensive food items in Mexican restaurants (Ramos-Elorduy & Pino 1989). *Liometopum apiculatum* Mayr of dry or semi-dry areas and *L. luctuosum* Wheeler (recorded as *L. occidentale* var. *luctuosum*) of wooded areas are reported to differ in flavour (Conconi 1982). In Mexico, brood of *L. apiculatum* and *Pogonomyrmex barbatus* (F. Smith) are used as cooked food while the “repletes” of *Myrmecosystus melliger* Forel and *Myrmecosystus mexicanus* Wesmael are eaten directly (Bodenheimer 1951; Ramos-Elorduy 2006). In ancient times, *M. melliger* was used by Mexicans to produce a sacred wine (Ramos-Elorduy & Pino 1989).

In some parts of Africa, worker ants of *Camponotus* sp. are used as salad seasoning and relished for their sweet-sour flavour (Nonaka 1996). In southern and eastern Africa, particularly in Zambia and Zimbabwe, winged sexual stages of *Carebara vidua* F. Smith are collected after the nuptial flight as they emerge from their nests after heavy rains and eaten raw or cooked by boiling, roasting or frying (Skaife 1979; Mbata 1995). The nests of this ant species are located only in termite mounds. In Congo, winged adults of *C. vidua* and all stages of *Oecophylla* ants are used as food (DeFoliart 2002 and references therein).

Consumption of ants by ethnic groups in parts of Asia, Australia, Africa, South and Central America (Table 1) is characterised by the ready availability of populous tropical ant colonies such as *Oecophylla* and *Atta* spp., subsistence farming conditions and age-old traditions of ant collection, particularly during periods of high seasonal availability, such as ant nuptial flights (Chen & Alue 1994; Ramos-Elorduy 1997a, b; DeFoliart 2002; Yhoung-Aree & Viwatpanich 2005). The utilisation of different ant species appears to be related to their local, seasonal availability, low cost of harvesting, nutritional/medicinal values and appropriate socio-economic conditions, such as ethnic/religious customs (DeFoliart 2002; Ramos-Elorduy 2009). Factors conducive to the cultural evolution of entomophagy may be low agricultural employment opportunities (DeFoliart 2002), seasonal unavailability of fish/game as in parts of southeastern Colombia (Dufour 1987) and chronic malnutrition as prevalent in northern and northeastern Thailand (Yhoung-Aree & Viwatpanich 2005) and parts of Mexico (Ramos-Elorduy & Pino 2002). However, with the migration of people from rural to urban areas, insect-eating habits have spread as in Thailand (Yhoung-Aree & Viwatpanich 2005), and some ant-based food preparations (e.g., escamoles) have become gourmet food used in restaurants in South and Central America, USA and France (Conconi *et al.* 1984).

Larvae and pupae of *Oecophylla smaragdina* are used not only as human food but also as food for songbirds and as fish bait in Java, in Indonesia (Césard 2004). Poorer-quality brood of the same ant species is used as chicken feed, reportedly to enhance growth of feathers and flesh (Césard 2004).

Nutritive content of ants

A number of studies have estimated the protein and fat content of some edible ant species, particularly those belonging to genera *Atta, Liometopum, Polyrhachis* and *Oecophylla* (Dufour 1987; Conconi *et al.* 1984; Raksakantong *et al.* 2009). The respective protein contents of female reproductives (dry-toasted) of *A. sexdens* and *A. cephalotes* has been estimated to be about 40 g and 48 g, and the fat content about 35 g and 26 g, per 100 g of edible portion (Dufour 1987). Protein content of adult *Liometopum apiculatum* was 46 percent while those of larvae and pupae were about 37 percent and 53 percent (dry weight), respectively (Conconi *et al.* 1984). Adults and reproductives of *L. luctuosum* contained 38 percent and 42 percent protein, respectively (dry weight) (Conconi *et al.* 1984). Extracts of ants of the genus *Polyrhachis* contained about 30–70% protein (Cheng *et al.* 2001 and references therein). Workers and queens of *O. smaragdina* were found to be rich in proteins (about 37% and 53% respectively, dry weight), with the lipid content being higher in the queen caste (about 37%) than in workers (about 13%) (Raksakantong *et al.* 2009). Protein and fat contents of young ants (i.e., larvae and pupae) of *O. smaragdina* were estimated to be 12.7 g and 12.5 g, respectively, per 100 g of insects (dry/wet weight unspecified) (Yhoung-Aree & Viwatpanich 2005). The dried powder of the black ant *Polyrhachis dives* is documented to contain 57 g/100 g protein, 9.0 g/ 100g fat and 13 g/ 100 g volatile oil (Shen *et al.* 2006). The protein content of *O. smaragdina* ants is reported to be comparable to that of chicken eggs (Offenberg & Wiwatwitaya 2009); such high protein concentrations indicate that ants are excellent nutritive substitutes for conventional vertebrate meat, with the additional advantage of being less expensive and more abundant.

Carbohydrate content of the ant *Myrmecocystus melliger* is estimated to be about 78 percent, which is particularly high among insects (Ramos-Elorduy *et al.* 1997).

Reproductive adults of *A. mexicana* and brood of *L. apiculatum* are demonstrated to be rich in essential amino acids such as lysine, leucine, isoleucine, valine and phenylalanine (cf. values in WHO/FAO/UNU 1985), although *L. apiculatum* brood was found to have less methionine than recommended values (Ladrón de Guevara *et al.* 1995). Extracts of ants of the genus *Polyrhachis* contain more than 50 nutritional elements, including 26 kinds of amino acids (Cheng *et al.* 2001 and references therein). *Polyrhachis dives* dried powder is estimated to contain 77,000 IU/100g of superoxide dismutase (SOD) and also 18 amino acids, the most predominant being glutamic acid, glycine, and aspartic acid (Shen *et al.* 2006). The same species also contains 16 minerals, the most important to humans being K, Ca, P, Mg, Fe, Mn and Zn (Shen *et al.* 2006). Deficiency of micronutrients such as zinc have recently received attention since zinc deficiency not only causes stunted growth, retarded mental growth and debilitation in the immune system of children, but its deficiency in pregnant women can have serious consequences for their infants (Prasad 2010). *Polyrhachis dives* is widely regarded as a health food in China since it is a rich source of vitamin E, SOD, essential amino acids, unsaturated fatty acids, and minerals. Extracts of *P. lamellidens* F. Smith are also rich in aliphatic hydrocarbons, aliphatic alcohols, aliphatic fatty acids (particularly oleic acid) and steroids (Cheng *et al.* 2001).

High levels of polyunsaturated fatty acids (PUFA) are found in the immature stages of many holometabolous insects (Ramos-Elorduy 2008). With increasing interest in the health benefits (for instance, to immune function, inflammatory response and cardio-protective effects) derived from diets containing long chain omega-3 PUFAs (reviewed by Williams 2000), recent research has focused on the analysis of lipids and fatty acid composition of edible ants (Sihamala *et al.* 2010). *Polyrhachis dives* dried powder contains about 9.0 g/ 100g fat and 13 g/ 100 g volatile oil (Shen *et al.* 2006). Analysis of two hot-air dried edible ant species demonstrated triacylglycerol to be the major lipid component, and oleic acid the predominant fatty acid, in both *P. dives* and *O. smaragdina* (Bhulaidok *et al.* 2010: Sihamala *et al.* 2010). Fatty acid composition analysis of *O. smaragdina* queen ants has revealed high concentrations of PUFAs, with arachidonic acid being as high as 964 mg/100 g (Raksakantong *et al.* 2009). High PUFA concentration is also demonstrated in *P. dives* (Shen *et al.* 2006) and *P. lamellidens* (Cheng *et al.* 2001). Brood of *O. smaragdina* is found to be rich in vitamins and nutrients, particularly K (168mg per 100 g of insects), and low in sodium (50 mg per 100 g of insects, dry/wet weight unspecified) (Yhoung-Aree & Viwatpanich 2005). The high PUFA content reported in many ant species could be of immense human health benefit, since PUFA causes reductions in insulin resistance, blood lipids and blood pressure (Rasic-Milutinovic *et al.* 2007).

Table 2: Ant species used in the treatment of various human diseases in different countries

Country	Ant species	Disease treated	References
Africa	*Dorylus* spp.	Mandibles used for emergency wound suturing	Gudger (1925)
	Camponotus brutus Forel	Used for external treatment of wound	Lawal & Banjo (2007)
	Formica sp.	Used for external treatment of wound	Lawal & Banjo (2007)
	Oecophylla smaragdina (Fabr.)	Acidic secretion obtained by pressing the ant used as an aid to stimulate the gastric juices	Nkouka (1987); Bani (1995)
		Ants used as an aphrodisiac	Van Huis (2002)
	Oecophylla longinoda (Latreille)	Nest extract used for treatment of asthma and severe cough	Van Huis (2002)
	Pheidole sp.	Treatment of stomach problems	Van Huis (2002)
Australia	*Oecophylla smaragdina* (Fabr.)	Used as a remedy for cold and flu, headache	Lockhart (2000), Yen (2005); Crozier (2010) and reference therein
	Unidentified ants (*O. smaragdina*?)	Used to treat stomach troubles, headaches, and cough	DeFoliart (2002) and references therein

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Table 2 (*continued*)

Country	**Ant species**	**Disease treated**	**References**
China	*Polyrhachis dives* F. Smith (= *vicina* Roger)	Improved functioning of the immune system and enhanced blood circulation, reduction in pain and inflammation, rheumatoid arthritis, increase in milk production in lactating women, as treatment for asthma and for anti-aging. Used to increase appetite, provide pain relief, improve digestion and increase the number of white blood cells in cancer patients.	Liu (1991); Chen & Alue (1994)
	Polyrhachis lamellidens F. Smith	Found to be useful for arthritis and hepatitis	Kou *et al*. (2005), Liu & Jiang (2005); Jiang *et al*. (2008)
India	*Oecophylla smaragdina* (Fabr.)	Provides resistance against fatigue and sun's heat	Long (1901)
		Ant paste used as a remedy for myopia	Padmanabhan & Sujana (2008)
		Fumes obtained by rubbing ants used to get relief from symptoms of cold	Veeresh (1999)
		Stomach ache and cold	Posey, 1986 and references therein
		Oil (in which adult ants are dipped) used in the treatment of rheumatism, stomach infections, gout, ringworm, aphrodisiac	Oudhia (2002)
		Gout and joint pain, weakness resulting from prolonged fever due to typhoid, for prevention of gastritis	Kumari and Kumar (2009)
	Unidentified ant species	Mandibles of soldiers used as biodegradable sutures for internal surgery	Bhagwati (1997)
	Unidentified ant species	Mud from ant nest used for treatment of scabies	Wilsanand *et al*. (2007)
Latin America	*Myrmecosystus melliger* Forel	Ant venom used as cure for rheumatism, arthritis, hysteria	Ramos-Elorduy (2006)
		Ant honey used for healing bruised and swollen limbs, ear ache	DeFoliart (2002) and references therein
	Myrmecosystus mexicanus Wesmael	Ant honey used for ophthalmic cataracts	Conconi (1982)

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Table 2 (*continued*)

Country	Ant species	Disease treated	References
	Atta spp.	Treatment of tendinitis, tuberculosis, conjunctivitis, hemorrhage, asthma, tonsillitis, dizziness, warts, lack of appetite, oral wounds, aphrodisiac, bronchitis, adenitis, alcoholism	Costa-Neto & Oliveira (2000); Costa-Neto (2002)
	Atta sexdens (Linn.)	Tonsillitis, hoarseness, stomach ache, dyspepsia, chest palpitations	Branch & Silva (1983); Alves *et al*. (2008) and references therein
	Atta cephalotes (Linn.)	Ear ache, sore throat	Branch & Silva (1983); Alves *et al* (2008) and references therein
		Stomach ache, heart diseases, chest palpations	Alves (2009) and references therein
	Dinoponera quadriceps Santschi	Asthma	Alves (2009) and references therein
Myanmar	*Oecophylla smaragdina* (Fabr.)	Beneficial for menstruation, used as an ingredient in a cough expectorant	DeFoliart (2002) and references therein
Thailand	*Oecophylla smaragdina* (Fabr.)	Used for detoxification of blood, arresting hemorrhage during miscarriages, restoration of uterus and removal of any aftermath from the uterine canal after childbirth, stimulating pulse and heartbeat, relief for asthmatic symptoms and dizziness	Yhoung-Aree & Viwatpanich (2005) and references therein

USE OF ANTS IN TRADITIONAL ENTOMOTHERAPY

Ethnoentomology has revealed that apart from the consumptive value, some ant species are also remarkable for their medicinal value, predominantly in Asian and Latin American countries (Table 2) and to a lesser extent in Australia and Africa. The use of biodegradable sutures in the form of ant mandibles (composed of chitin, a complex protein carbohydrate material) for internal surgery was well known in ancient India (Rastogi & Kaphle 2008) and Africa (Gudger 1925). Soldiers of driver ants, *Dorylus (=Anomma)* spp. found in Africa and tropical Asia (Skaife 1979) have traditionally been used for suturing wounds. In India, in cases of intestinal perforations after laparotomy, the perforations were identified, approximated and then exposed to black ant soldiers with their pincer like jaws. Soldier ants were held so that the open mandibles gripped the opposing edges of the perforated intestinal walls. Once the mandibles snapped shut, the thorax and gaster of the ants were pinched off, leaving behind a series of clamped mandibles in place (Rastogi & Kaphle 2008).

Ammonia-like fumes produced by rubbing *O. smaragdina* were inhaled by Tamil labourers in India to relieve symptoms of the common cold (Veeresh 1999). Tribal people in Koraput District of Orissa eat the brood, reportedly to keep the body and mind cool in hot summer, and utilise *O. smaragdina* workers as food so as to improve their eyesight (Anon. 2009). Special medicated oils from these ants are used in the treatment of rheumatism, gout, ringworm and other skin diseases, depending upon the nature of the oil (such as mustard, sesamum and jasmine oil) used as a base (Oudhia 2002) (Table 2). The Paniyan tribes of Kerala in India use the mud taken from the interior of unidentified ant nests to treat rabies (Wilsanand *et al.* 2007). *Oecophylla smaragdina* is also documented to be useful in the treatment of cold and cough in Australia (Crozier 2010 and references therein).

In Brazil, the leafcutter ants *A. cephalotes* and *A. sexdens* are used in the treatment of a large variety of diseases (Costa-Neto 2002; Alves 2009). Ants have been used in China as complementary and/or alternative medicine to treat a wide range of medical conditions and diseases for more than three thousand years (Piao *et al*. 2009). They are utilised for a variety of purposes including improvement of the immune system, blood circulation and metabolism, reduction in inflammations and pain, treatment of asthma and rheumatoid arthritis, and slowing down of the aging process (Chen & Alue 1994). However, only a few of the attributed medical properties and treatments are supported by scientific evidence (Jiang *et al.* 2008). More than 30 health food products containing *P. dives* ants have been approved in China since 1996 (Shen *et al.* 2006). Extract of *P. dives* is used as a sexual stimulant, to enhance immunity and to treat rheumatism (Liu 1991; Chen & Alue 1994). Another Chinese medicinal ant, *P. lamellidens*, found throughout southern China and Taiwan, has been extensively used as folk medicine for the treatment of rheumatoid arthritis, chronic hepatitis and aging (Cheng *et al*. 2001, and references therein). Most ant species used in entomotherapy also comprise part of the normal diet of local people.

COMMERCIAL HARVESTING AND MARKETING OF ANTS

Commercial harvesting and sale of edible ants and their brood is reported in many rural markets of Thailand, Indonesia, China and Mexico, indicating the productive use value of ants (DeFoliart 1989; Ramos-Elorduy 1997a,b; Sribandit *et al.* 2008). Ant medicines currently sold in China include wines, syrups, powder products and capsules (Chen & Alue 1994; Bhulaidok *et al.* 2010). Ant products containing *P. dives* are exported from China to south-east Asian countries including South Korea, Japan and Thailand (Shen & Ren 1999). Reproductive ants of the *Eciton* genus, and leafcutter ants, *A. mexicana* and *A. cephalotes* are sold in many towns of Mexico, while the leafcutter ants are also in demand on the international market (Ramos-Elorduy & Pino 2002). While escamoles (larval stages of *L. apiculatum* and *L. luctuosum*) are sold in Mexico (Ramos-Elorduy 2006), *O. smaragdina* brood is sold in Thailand (Sribandit *et al.* 2008).

Annual sale of ant foods for human consumption in China amounted to approximately $100 million (DeFoliart 1999) about two decades ago. A more recent study of the socioeconomic impact of *O. smaragdina* collection and marketing in Thailand revealed a daily income of US$12 per working day during the 4–5 month harvesting season (Sribandit *et al.* 2008). About 30 percent of the family income of ant collectors in Thailand was met from commercial use of *O. smaragdina*. Collection of *O. smaragdina* from one province alone yielded an income of about US$620,000 per year (Offenberg & Wiwatwitaya 2010). Thus, ecologically dominant ant species such as *O. smaragdina* provide multiple benefits, firstly by pest suppression (Rastogi 2004; Van Mele 2008), secondly by converting pests into a protein-rich food (Offenberg & Wiwatwitaya 2009, 2010) and thirdly by contributing a source of income (Yhoung-Aree & Viwatpanich 2005; Sribandit *et al.* 2008).

ANTS AS POTENTIAL SOURCES OF PHARMACEUTICALS AND ANTIBIOTICS

Many species of ants are regarded as important sources of pharmaceuticals (Blum 1992; Mackintosh *et al.* 1995; Majer *et al.* 2004). Recent research demonstrates that social insects including ants possess well developed immune systems and disease resistance ability (Rosengaus *et al*. 1999; Fefferman *et al*. 2007; Stowe & Beattie 2008; Wilson-Rich *et al*. 2009). Antibiotics produced by the paired metapleural glands of ants are secreted externally (Beattie *et al*. 1986) and provide protection against pathogenic fungi and bacteria (Fernandez-Marin *et al.* 2006; Poulsen *et al.* 2006). It is suggested that high microbial parasites and pathogen pressure has led to the evolution of immune proteins in social insects (Viljakainen *et al.* 2009) including ants (Schluns & Crozier 2009).

A variety of antimicrobial (bactericidal/fungicidal) compounds which provide protection against environmental pathogens have been isolated and characterized from social insects, particularly ants (see review by Schluns & Crozier 2009). Leafcutter ant species are documented to spread metapleural-gland secretions, while grooming themselves, their nest mates including the queen, and their fungal gardens (Fernandez-Marin *et al.* 2006). Two antibacterial peptides synthesized in the ant *Myrmecia gulosa* (Fabr.) in response to bacterial infection have been characterised (Mackintosh *et al.* 1998). Extracts of the Eurasian ant, *Formica aquilonia* Yarrow are found to exhibit antioxidant and anti-inflammatory properties (Piao *et al*. 2009). Also, fifteen novel peptides exhibiting antibacterial and insecticidal properties have been isolated from the venom of the predatory ant *Pachycondyla goeldii* (Forel) (Orivel *et al*. 2001).

Fungus-growing ants are found to ward off fungal parasites by means of mutualistic, antibiotic-producing bacteria which they harbour on special structures located on their cuticle (Currie *et al*. 2006). Recent studies demonstrate that ant-associated actinomycetes are highly diverse and are rarely specific in their inhibition of other microbes (Sen *et al.* 2009). Investigations of the proteome of the obligate intracellular endosymbiotic bacteria *Blochmannia floridanus,* found in the gut of carpenter ants, may lead to the production of new antibiotics that can target Gram-negative bacteria (Zientz *et al*. 2006; Ruiz *et al*. 2008). However, such studies on ant host-microbe mutualisms are in their infancy.

Pharmacological investigations and clinical trials indicate that certain components of the ant *P. lamellidens* are active in the treatment of diseases including arthritis, rheumatism, liver ailments and asthma (Cheng *et al*. 2001 and references therein). Extracts of the *P. dives* demonstrate inhibition in ferric-nitrilotriacetate-induced nephrotoxicity in laboratory rats (Ma *et al.* 1997). Further, the analgesic and anti-inflammatory activities of extracts of *P. lamellidens* have been demonstrated by Kou *et al*. (2005) and also by Liu and Jiang (2005), while from the same species Jiang *et al*. (2008) have identified two polyketides, suggested to have potential in the treatment of rheumatoid arthritis. These studies provide scientific evidence supporting the traditional uses of medicinal ants in the treatment of various diseases associated with inflammation.

Recent studies (Siri & Maensiri 2010) show that natural silk fibres of the weaver ants *O. smaragdina* can serve as a cell matrix for cell adhesion and thus have application in tissue engineering and wound healing.

CONCLUSIONS

The family Formicidae appears to be a key taxon in providing ecosystem goods and provisioning services. Ant species can feed on plant exudates, honeydew (Cook & Davidson 2006) and a variety of arthropods, including many economically important insect pests of crops (Agarwal *et al.* 2007). They thereby convert unavailable plant and animal resources efficiently into edible form. Entomophagy is suggested to serve as a significant measure not only in obtaining protein-rich, inexpensive foods (Robert 1989; Ghaly & Alkoaik 2009; Srivastava *et al.* 2009), often considered delicacies (DeFoliart 2002), but also in avoiding mineral deficiencies, particularly of zinc and iron (Christensen *et al*. 2006). Ant colonies are populous, easily located and have a relatively high multiplication rate compared with vertebrate meat sources. Ants constitute an easily digestible, good source of nutrition and can play a critical role in meeting the food requirements of the world's increasing human population, as part of the multi-pronged approach required (Trewavas 2001; Godfray *et al.* 2010). However, an essential prerequisite is to overcome the widespread phobia of entomophagy and the reluctance to shift from vertebrate-based diets (Yen 2009a).

Since biomagnifications may increase pesticide content in edible insects procured from pesticide-sprayed agroecosystems, organic farming needs to be encouraged. Another aspect to be kept in view is the potential impact of large-scale ant harvesting activities on the ecosystem, since ants occupy a variety of trophic levels as herbivores, predators, scavengers, seed harvesters, *et cetera*.

Traditional collectors collected the brood for individual/family consumption. They were prudent harvesters and, while harvesting colony fragments, ensured sustainability (Conway 1985, 1990; Sribandit *et al.* 2008). However, careless overharvesting of naturally-occurring ant colonies for commercial purposes by modern untrained collectors has led to a decline in the populations of coveted edible/medically-important ant species such as *O. smaragdina* populations in Java (Césard 2004), and raised similar concerns in China (Wang *et al*. 2001) and Thailand (Sribandit *et al.* 2008). Meanwhile, *L. apiculatum, M. Melliger* and *M. mexicanus* are now on the Mexican list of threatened species due to overharvesting (Ramos-Elorduy 2006).

Just as increasing demand for insect food has already initiated farming of crickets *Gryllus bimaculatus* De Geer and bamboo moths *Omphisa fuscidentalis* Hampson in Thailand and adjoining countries (Yhoung-Aree & Viwatpanich 2005), ant-farming appears a feasible option to provide a source of livelihood along with cheap, protein-rich, renewable food. Some species such as *A. cephalotes* and *A. mexicana* are already proto-cultivated based on the experience and in-situ conservation knowledge of rural people in Mexico (Ramos-Elorduy 2009). Conservation of edible ant species would however need basic knowledge of their ecology, behaviour, demography and distribution.

Although biochemical and pharmacological evidence is available for only a few ant species, the use of ants for similar ailments in a number of countries does indicate significant medical utility. For instance, *Oecophylla* spp. are used for enhancement of immunity, treatment of gastric problems, asthma/cough and cold, in India, Australia and Africa (Table 2). A number of ant species are used for the treatment of arthritis. These include *O. smaragdina* in India, *P. dives* and *P. lamellidens* in China, and *M. melliger* in Mexico—all formicines, raising the question of whether their pharmacological attributes are characteristic of the subfamily. Similarly, several ant species belonging to the genus *Atta* are also used for the treatment of cold and cough. More ethnobiological studies therefore need to be undertaken in the various tribal areas of the world.

Keeping in view the energy conversion efficiency of insects relative to livestock, insects are environmentally-friendly alternative protein sources (Vogel 2010). Consequently, the policy guidelines currently being developed by the UN Food and Agriculture Organization also aim to encourage the use of insects as part of a global strategy to meet the world food security challenges. Moreover, vertebrate meat-based food systems require more resources and are not environmentally friendly (Pimentel & Pimentel 2003). While some of the economic benefits are presently known, many more potential uses of ants in human health and medicine have been discovered in the last decade. Further research therefore should be focused on investigation of nutritional composition, immune defence mechanisms and pharmacological properties of different developmental stages and adult ant castes. Attention should also be given to the prospects for farming ant colonies, and conserving ants in natural and managed ecosystems. These studies should be targeted particularly at traditionally utilised ant species including those belonging to the genera *Oecophylla, Polyrhachis* and *Atta*, since their use and potential as food and medicine is already well documented. However, it may be worthwhile to explore the entomophagy potential of other species of ecologically dominant ant species which feed on homopteran honeydew, extrafloral nectar and/or insect pests, since it is demonstrated that nutrient content and particularly lipid content of insects varies with their habitat and diet (Raksakantong *et al.* 2009). Since ant colonies could provide economically valuable resources to mankind, a major future challenge is to investigate how ant biodiversity can be maintained in anthropogenically-disturbed ecosystems. Ant biodiversity holds remarkable potential for commercial bio-prospecting, and for providing future nutritive and pharmaceutical benefits to mankind.

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