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Biology and management of the red-legged ham beetle, *Necrobia rufipes* DeGeer (Coleoptera: Cleridae)

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ABSTRACT

The red-legged ham beetle, *Necrobia rufipes* DeGeer (Coleoptera: Cleridae), is an important world-wide insect pest of stored-products of animal origin, but it can also infest a wider range of commodities. A review detailing the biology of *N. rufipes* including the morphology, development and reproduction of this pest is presented. This review also illustrates various aspects of its integrated control and summarizes the current knowledge for *N. rufipes* management, given that there were additional data that have been produced towards this direction during the last decade. Furthermore, this paper identifies potential areas of further research on *N. rufipes* for practical implementation.

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1. Introduction

The beetles of the family Cleridae are a diverse group of insects with wide geographic distributions. Corporaal (1950) catalogued 3366 described species worldwide, while later Opitz (2002) listed 291 species in North America. Clerid beetles are economically important, due to the fact that most species are predaceous on other insects in both adult and larval stages (Stephens, 1832; Csiki, 1900; McNamara, 1991). The vast majority of the species in the family Cleridae occur on plants and tree trunks, but species of *Necrobia* are scavengers and can be found infesting carcasses and hides of vertebrate carrion. Larvae of Cleridae are mostly predacious and feed upon wood- and bark boring beetles (Yadav and Dange, 1989). Many specimens have been recorded on flowers, vegetation, dead and dying trees infested with borers, and bones and skin of dead animals (Knull, 1951).

Necrobia rufipes DeGeer is saprophagous and destructive to stored products of animal origin. *Necrobia rufipes* is the most common beetle species that infests dried meats that are aged for periods longer than 3 months (Sekhon et al., 2009; Hasan and Phillips, 2010; Hasan et al., 2016). It is also one of the most destructive pests of copra. In addition, it has been found feeding on cheese, dry-cured ham, bacon, fish and salt fish, dried egg yolk, bones and bone meal, carrion, dried figs, palm nut kernels, and guano (Hasan and Phillips, 2010). The species of this genus are able to develop on dead fatty animal matter, sometimes on oily plant substances, or on larvae of other carrion visitors. *Necrobia rufipes* has also been repeatedly found in Egyptian mummies (Hope, 1834; Crowson, 1964; Gerstmeier, 1998). The objective of this current article is to provide a review of published literature to date relevant to the biology and management of *N. rufipes* as a pest of high-value stored products.

Simmons and Ellington (1925), who identified the insect as a pest of dry-cured ham, dried fish, copra, cheese, nuts and figs in many parts of the world, undertook one of the first inclusive scientific studies of *N. rufipes*. The products or groups of products that have been reported to be infested by *N. rufipes* are listed in several publications (Table 1).

It has been reported that *Necrobia* spp. infest salted or smoked fish during storage. Laboratory investigation of dried fish such as *Citharinus, Clarius, Heteroles* and *Synodontis* spp. in Nigeria revealed a positive correlation between the lipid content of fish and the level of infestation by *N. rufipes* (Osuji, 1974).

A comprehensive scientific study of *N. rufipes* was undertaken by Hamlin et al. (1931), who classified the insect as a pest of grain, grain-based crops, and more than 20 different types of nuts, fruits, and candies from the agricultural system in the state of California, USA. They also described the economic consequences of infestations through infested products that have been returned. This is a cosmopolitan species that probably originated from the Palearctic region and was introduced to the USA. Aitken (1975), Buchelos (1980) and Buchelos and Athanassiou (1993) provide evidence that this species can be frequently found in various amylaceous commodities and also in dried fruit. Levinson and Levinson (1978) reported that *N. rufipes* can also feed on other insect species.

2. Systematic position

Necrobia rufipes has historically been placed in three different families (Cleridae, Dermestidae and Tenebrionidae) due to its unusual appearance and behavior (Klug, 1842; Abeille, 1895; Solervicens, 2005). The first antennomere is thick and slightly bent, and the antennae contain five basal, reddish-brown segments and 5 black apical segments (Koç et al., 2020). Adults range from 3.5 to 7.0 mm in length (Haines and Rees, 1989).

Necrobia rufipes is the species with the highest economic importance among the other members of the family Cleridae, whose larvae are typically predaceous and often beneficial as enemies of economic insects, including the cigarette/tobacco beetle, *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae), and many species which attack forest trees (Koç et al., 2020).

De Geer published the original description as *Clerus rufipes* in 1775. In 1796, Latreille classified the genus *Necrobia*. Mulsant and Rey (1863) placed the species in the genus *Agonolia* and also listed *Clerus rufipes* De Geer, *Dermestes rufipes* F., *Corynetes rufipes* Herbst, and *Necrobia rufipes* De Geer, etc., indicating the four genera to which this species had been referred (Kim and Jun 2006).

3. Identification features

Egg: The egg of *N. rufipes* is approximately 1 mm in length and 0.25 wide, tapered, roundly pointed at both ends and slightly curved (Fig. 1). It is smooth, shiny, translucent, and is glued in place when oviposited. The eggs are usually deposited in clusters. Those laid by old females often partially collapse laterally within a few hours after being deposited, and such shrunken eggs do not hatch (Simmons and Ellington, 1925).

Larvae: Larvae contain three pairs of jointed legs, which are moderately hairy. Most of the body is creamish-grey with mottled violet-grey markings on the upper surface. The head and upper surfaces of the first thoracic segment and the last large abdominal segment (the ninth) contain brown hardened plates; the second and third thoracic segments also consist of tiny brownish plates. A plate on the last large abdominal segment has two horn-like protuberances, which curve strongly upwards. It is very difficult to distinguish from closely related species of Cleridae (Simmons and Ellington, 1925).

Pupae: Several days after the cocoon is formed, the larva contracts in length, and the body consequently becomes more robust; the head assumes a fixed attitude at right angles to the body axis, and the insect becomes a pre-pupa. After, the last larval skin is cast, the pupa appears in the cell (Simmons and Ellington, 1925).

Adults: The average body length is 4.5 mm. The upper surface of the body (head, thorax, elytra) is shiny, metallic and bluish-green. The underside of the abdomen is entirely dark blue. The legs are bright reddish-brown or orange, and the antennae are predominantly reddish-brown with a dark brown or black club at the tip. There are stiff bristle-like hairs present at the sides of thorax and elytra. Hitchcock (1963) noted that elytral setae on females are forward-pointing, a sexually dimorphic character for adults, and that males respond to these setae during sexual behavior. Adults of *N. rufipes* can be distinguished from adults of similar species by the coloration described above: *N. violacea* (L.) has black or bluish legs and antennae; and *N. ruficollis* (F.) has a reddish-brown thorax and

Table 1
Commodities and habitats associated with *N. rufipes* and the countries of origin.

Items associated	Country	Reference
Hides and skins	Argentina	Grillo-Torrado et al. (1980)
Museum collections, Copra	India	Kumari et al. (1992); Adolph and Soans (1969)
Bladders (for sausages)	Argentina	Grillo-Torrado et al. (1980)
Dried Fish	Bangladesh, Mali, Senegal, Indonesia, Zambia	Bhuiyan and Saifullah (1997); Guillon (1976); Mallamaire (1957); Madden et al. (1995); Proctor (1972)
Shrimp, Palm kernel	Nigeria	Bello-Olusoji et al. (2006); Allotey and Kumar (1989)
Pet food	USA, Brazil, Italy, Europe	Roesli et al. (2003); Gredilha and Lima (2007); Savoldelli et al. (2018); Stejskal et al. (2015)
Ham/Bacon	USA	Sekhon et al. (2009); Hasan and Phillips (2010); Hasan et al. (2016)
Copra	Canada	Corbett et al. (1935); Judd (1949), Mazka (2006)
Drying carrion	S. Africa, Peru, Iran	Louw and Linde (1993); Iannacone (2003); Fakoorziba et al. (2017)
Fungus Eater, Timber	Australia	Chuku et al. (2007); Brimblecombe (1938)
Blow and Flesh Flies	Egypt	Nagat et al. (1990)
Deck of Ship	Japan	Muarata et al. (2007)
Tanneries	Iraq, USA, Poland, England	Jarjes et al. (1988); Walker (1944); Martynowicz et al. (1976); Corbett (1915)
Storage Products	Russia, Tonga, Germany, Fiji	Kosolapova (1970); Laborius et al. (1980); Ruhdolf (1935); Lever (1945); Vaivanijkul (1973)
Textiles	Hong Kong	Weidner (1967)
Stored Cereal products	Tonga and Samoa	Laborius et al. (1980)
Chestnut	Brazil	Grdilha et al. (2005); Gredilha and Lima (2007); Pratissoli (1997)
Figs	Ireland	Johnson (1920)
Animal feed	Indonesia	Suryoadikusumo (1978)
Corpses	South Africa	Louw and Linde (1993)
Spices	China	Cheng-de and Yong-qing (2007)
Animal Carcasses	Spain	Pinero (1997)
Foodstuffs	Saudi Arabia	Menier (1986)
Currants, Sultanas, Flour, Grains	Greece	Buchelos (1980); Buchelos and Athanassiou (1993, 1998, 1999)

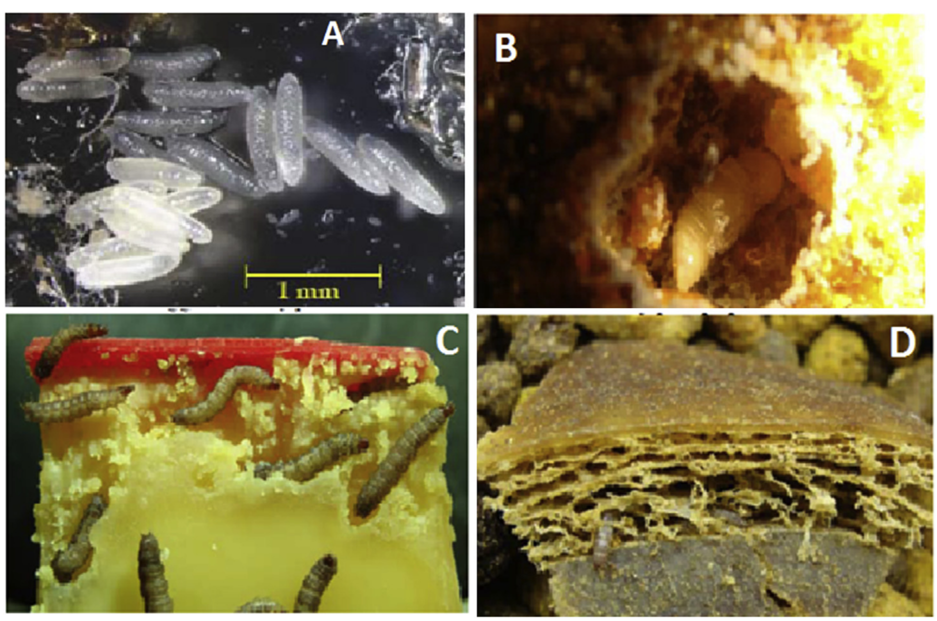

Fig. 1. *Necrobia rufipes* eggs (A), pupa in cell (B); larvae in cheese (C) and larvae in dry-cured ham (D).

wing base (Simmons and Ellington, 1925).

4. Sampling, occurrence and distribution

Necrobia rufipes has a cosmopolitan distribution. Roesli et al. (2003) reported the abundance of *N. rufipes* while surveying eight Kansas (USA) retail stores belonging to a pet store chain. Stejskal et al. (2015) reported common association of *N. rufipes* with pet food in European countries. Both larvae and adults of *N. rufipes* cause considerable damage to stored copra (dried coconut),dry-cured ham, cheese, dried fish, and other products that are rich in protein content (Simmons and Ellington, 1925; Gonzalez et al., 1957; Ashman, 1962). *Necrobia rufipes* is also a facultative predator and preys on the larvae of *L. serricorne*, the merchant grain beetle, *Oryzaephilus mercator* (Fauvel) (Coleoptera: Silvanidae), and the corn sap beetle, *Carpophilus dimidiatus* (F.) (Coleoptera: Nitidulidae) (Simmons and Ellington, 1925; Ashman, 1962). Larvae of *Oryzaephilus* spp. were frequently captured in pitfall traps in the stores studied by Roesli et al. (2003), suggesting that suitable prey for *N. rufipes* was available in the pet-food stores. Furthermore, *N. rufipes* can breed on animal carcasses (De Souza and Linhares, 1997). Roesli et al. (2003) captured 450 *N. rufipes* larvae in a pitfall trap placed behind a kick plate. Apparently, the trap was near a dead cadaver of a mouse, and the mouse cadaver was completely covered with *N. rufipes* larvae and adults (Roesli et al., 2003).

The abundance and distribution of *N. rufipes* have been reported in different countries including France (Taschenberg, 1906), Australia (Hinton, 1945), Ceylon (Cooke, 1932), Norway (Somme, 1962), Ireland (Johnson, 1920), Greece (Buchelos, 1980; Buchelos and Athanassiou, 1993, 1998, 1999), Germany (Schenkling, 1900), the United States of America (Downie and Arnett, 1996), and Galicia (Iberian Peninsula) (Lauffer, 1905; Valcärcel and Piloña, 2001).

5. Host range

The biology of *N. rufipes* has been extensively studied using various diets including copra (Olds, 1937; Gonzalez et al., 1957; Ashman, 1962; Nalinakumari and Mammen, 1998), dried fish (Ashman, 1962; Osuji, 1975; Lambkin and Khatoon, 1990; Bhuiyan and Saifullah, 1997), palm kernels (Ashman, 1962), dry-cured ham (Simmons and Ellington, 1925) and house fly maggots (Scott, 1919). *N. rufipes* is associated with rotting meats, fish and cheese, cured ham and bacon, mammal tissue, guano, bone meal, coconut, garlic, grains, silk, cotton, rattan and salt (Lever, 1945). However, it does not feed on many of these materials. It instead feeds on other pests that infest products or decaying animal matter (Peck and Thomas, 1998). It is a known predator of the cheese skipper, *Piophila casei* (L.) (Diptera: Piophilidae), and larvae of Calliphoridae and Dermestidae (Simmons and Ellington, 1925). It also displays cannibalistic behavior in the absence of other sources of nutrients. A living specimen of *N. rufipes* was once collected in the skull of a mummy in Egypt (Champollion-Figeac, 1814; Knull, 1951). Mallis (1997) provided an overview of life history, development and control techniques for *N. rufipes*, while Simmons and Ellington (1925) reported a more exhaustive life history and many observations of behavior in adult and larval stages. Feeding by larvae and adults of *N. rufipes* causes quantitative loss of dried cured fish, and also leads to fragmentation and quality losses due to contamination by insect bodies and cast skins. When associated with *Dermestes* infestations, *N. rufipes* is usually in the minority but its contribution to the total damage may be significant (Odeyemi, 1997). Initial infestation is usually due to invasion by flying and crawling adults, which lay their eggs on the partially or fully dried fish, or other related materials. Fly-screens around and over fish drying racks will reduce beetle infestation pressure during processing. Similarly, during storage and transport, the use of clean good-quality sacks will slow down rates of immigration of *N. rufipes.* Osuji (1975) found that cross-infestation by *N. rufipes* was reduced when jute sacks were lined with polyethylene and thick brown paper.

6. Mass rearing

Information on the dietary requirements of *N. rufipes* is available in numerous studies (Scoggin and Tauber, 1949, 1951; Lall, 1958; Shiromany, 1961; Paul et al., 1962; Ashman, 1962; Osuji, 1977; Nalinakumari et al., 2001; Hasan and Phillips, 2010), including the effects of high density and cannibalism on yield (Ashman, 1962; Osuji, 1975; Rakowski and Cymborowski, 1982). However, a newer protocol for mass-rearing of *N. rufipes* in the laboratory was developed that facilitates the production of large numbers of insects with minimal handling (Fig. 2) (Hasan and Phillips, 2010). In this protocol, a culture medium comprised of finely ground (150 μm) dried fish, dry dog food and pieces of dried cured ham was found to be much more effective for mass rearing of *N. rufipes*, as compared to other published and unpublished rearing methods (Hasan and Phillips, 2010). When reared on this medium with initial colonies of 200 adult beetles of mixed sex, there was more than a three-fold increase in *N. rufipes* adult populations from the original numbers over a 7–8 week period. In addition, the benefit of this culturing technique is that it promotes undisturbed pupal cell formation in vials that minimizes cannibalism.

7. Biology

The minimum incubation period for eggs ranges from 4 to 6 d during warm weather (mean daily temperature between 21.7 and 31.7 °C). Larvae molt two or three times, hence, they pass through three or four instars, while complete larval development lasts approximately 17 d at 32 °C and 75% relative humidity (r.h.). Fully-grown larvae that infest smoked meat migrate from the greasy material in which they feed to seek dark and dry locations such as crevices in which they build their pupal chambers (Hasan and Phillips, 2010).

The adults and larvae are markedly predatory and cannibalistic. They often eliminate infestations of *P. casei*, by preying on the maggots (Simmons and Ellington, 1925). Adult ham beetles eat adults of their own species, as well as eggs and larvae, even when other prey is available. In our rearing, we observed that the newly hatched larvae feed on unhatched eggs of their own species as well as the eggs of the hide beetle, *Dermestes maculatus* DeGeer (Coleoptera: Dermestidae) (Hasan and Phillips, 2010). These researchers also reported that the pupal chambers are constructed with a white substance that is emitted from the mouth of the larva in frothy droplets that harden as soon as they are deposited. Pupation sometimes takes place without the protection of a cell, but exposed pupae are readily eaten by adults. In fact, adults sometimes break into pupal cells and eat the pupae. The cocoon may be completed within 24 h, and is formed by filling in the open boundaries of the crevice that is chosen for pupation within a wall. During the process of cell building, the larva is usually curled in the cell, although sometimes the enclosure is large enough to allow it to extend its length. At times, cocoons are broken into by adults, and the occupants are devoured. It is not uncommon for two larvae to enclose themselves in a common cell. Larvae have been observed to cease construction work and remain motionless, apparently as a means of protection, for several minutes while other larvae crawl on the outside of the cocoon. About 13 days are spent in the pupal cell, including portions of the adult and larval periods as well as the pupal period. Adults may remain within the cell for a day or two after they become fully pigmented. They emerge by chewing an irregular hole in the wall of the cell. Adults mate shortly after emergence and at frequent intervals during the oviposition period. The pre-oviposition period may be as brief as 2 d. The eggs are laid in batches, often with periods of a few days to 6 weeks or more between batches (Hasan and Phillips, 2010).

Simmons and Ellington (1925) reported that the time period from when the eggs hatch to the adult in warm weather may be as short as 30 d, including 17 d as growing larva and 13 d within the cocoon. Gonzalez et al. (1957) reported that *N. rufipes* required 54 and 13.5 d for larval and pupal periods respectively when rearing on copra. Osuji (1975) stated that the total developmental periods in *N. rufipes* vary from 52.2 to 98 d when insects are reared on salted dried fish. Canete and Gapasin (1980) and Nalinakumari and Mammen (1998) investigated the life table characteristics of *N. rufipes* on different varieties of copra and found that the total developmental periods vary from 59.6 to 72.6 d. Bhuiyan and Saifullah (1997) studied *N. rufipes* reared on the mixture of dried fish and copra and reported that 45 d were required to complete the total developmental period. Osuji (1977) reported that the total developmental period of *N. rufipes* was 107 d and 47 d when rearing on copra and dried fish respectively at 31 °C and 87% r. h. Several researchers investigated the fecundity in *N. rufipes* under different

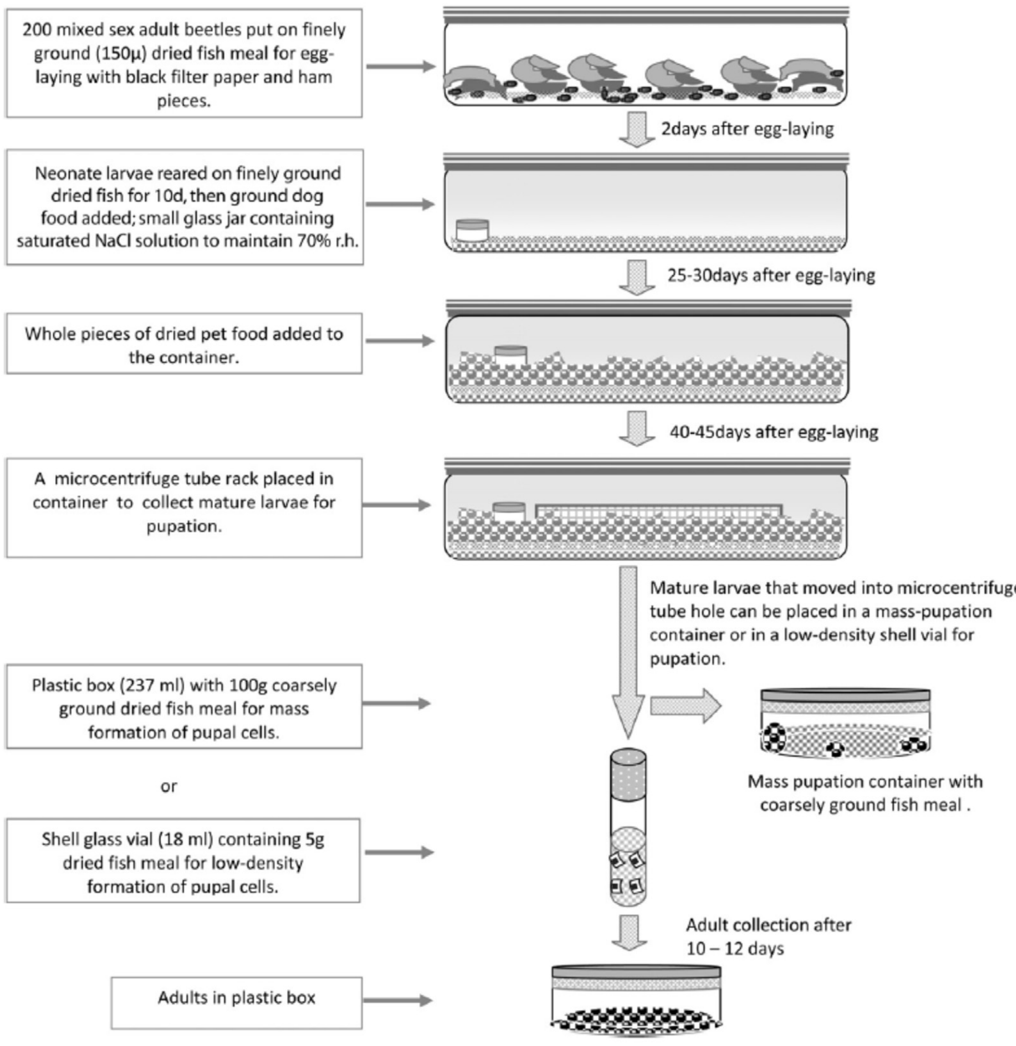

Fig. 2. Schematic diagram for mass-rearing *N. rufipes* in the laboratory at 27 °C, 60–70% r. h., and under a light regime of 16 h:8 h (L:D) (reproduced from Hasan and Phillips, 2010).

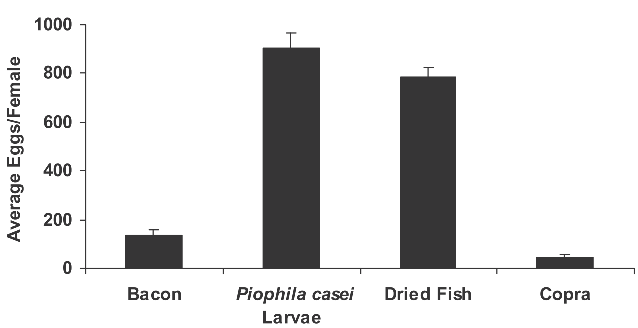

Fig. 3. Mean number of eggs (±SE) laid by a single *N. rufipes* female developing in different host foods [Based on: Simmons and Ellington (1925); Bhuiyan and Saifullah (1997); Nalinakumari and Mammen (1998)].

hosts and maximum eggs (906) were recorded while rearing on *P. casei* larvae followed by dried fish (784), bacon (137) and copra (43) (Simmons and Ellington, 1925; Bhuiyan and Saifullah, 1997; Nalinakumari and Mammen, 1998) (Fig. 3).

8. Ecology

The life history of *N. rufipes* varies considerably according to climatic conditions, as there are several biotic and abiotic factors that affect the biology of this species (Table 2). The optimum temperature for the development of *N. rufipes* is in the range of 30–34 °C, and the minimum temperature is 22 °C (Simmons and Ellington, 1925). On the other hand, the maximum temperature limit for its development is not known, but temperatures above 40–42 °C are likely to deter or prevent its development (Ashman, 1962). Hu et al. (2020) recently established the rate of development of *N. rufipes* from egg to adult for a range of temperatures from 22 °C to 36 °C. While a lower population development threshold was estimated at 22.0 °C for *N. rufipes*, this value is higher than those recorded for many other stored product beetles (e.g., Howe, 1965; Stejskal et al., 2019). This species needs an equilibrium r. h. of 50% or above (Ashman, 1962). *Necrobia rufipes* can therefore become a pest in tropical and subtropical climates, especially if conditions are rather humid. This species is usually associated with infestations of *Dermestes* spp., as its habitat requirements are similar to those of the tropical species of *Dermestes*, and it benefits from the availability of *Dermestes* larvae and eggs as prey (Odeyemi, 1997).

Table 2
Comparative studies for the developmental periods in *N. rufipes*.

Diets	Developmental periods (days)	Temperature and r.h.	References
Dried fish	30	Warm weather	Simmons and Ellington (1925)
Copra	58.5	30 °C, 64% r.h.	Gonzalez et al. (1957)
Salted dried fish	52.2 to 98	30 °C, 75–80% r.h.	Osuji (1975)
Copra	59.6	27.5 °C, 75% r.h.	Canete and Gapasin (1980)
Copra	72.4	–	Nalinakumari and Mammen (1998)
Dried fish & Copra	45	30 °C, 80% r.h.	Bhuiyan and Saifullah (1997)
Copra	107	31 °C, 87% r.h.	Osuji (1977)
Dried fish	47	31 °C, 87% r.h.	Osuji (1977)
Copra	58 to 103	28 °C, 75–80% r.h.	Ashman (1962)
Copra, fishmeal	37–112	28 °C, 75–80% r.h.	Ashman (1962)
Carpophilus dimidiatus larvae	37.9	28 °C, 75–80% r.h.	Ashman (1962)
Dried fish, pet food, ham	61.6	27 °C, 65% r.h.	Hasan and Phillips (2010)

-Not available.

9. Pest status

Necrobia rufipes is a major pest of stored products of animal origin, particularly of those that have reportedly low moisture content (Ong and Roadhouse, 1922). Environmental conditions such as rain, elevated temperature and humidity in and around dry curing ham facilities positively influence the level of pest pressure. Adults of *N. rufipes* feed on the cured meat while the larvae burrow in the meat and/or fat. The larvae are commonly referred to as a “ham borer” (Simmons and Ellington, 1925).

Kumari et al. (1992) investigated the occurrence of damage in nature that is caused by pests of stored copra in Kerala, India, and *N. rufipes* was reported to be the most serious pest of copra in the majority of warehouses that were surveyed. The reports by earlier workers from different countries presented different reports about the status of these insects as pests of copra. Early reports indicate that *N. rufipes* was a major pest of copra in different regions including Sumatra (Rutgers, 1918), Gilbert and Ellice Islands (Peter, 1974), Guyana (Rai and Singh, 1977) and West Samoa (Laborius et al., 1980). As indicated above, it is primarily predaceous on other insect species. However, when prevailing conditions are suitable for its development and population growth, *N. rufipes* can cause major damage to museum objects, where infestations should be treated swiftly (Phillips et al., 2011). Most species of Cleridae are predators of various species of necrophagous insects, but *N. rufipes* is the exception to the rule. Adults and larvae feed on various substrates of animal and plant origin, but they are also necrophagous and even cannibalistic. Practically, it is the only harmful species (i.e. in terms of economic importance) among those of the Cleridae family. In tropical regions, *N. rufipes* is a pest of copra that is stored in warehouses (Osuji, 1977). It can also damage insect collections (Adolph and Soans, 1969). The adults are proficient at flying, which can further contribute to its expansion. Leavengood (2008) reported that *N. rufipes* adults are attracted to ultra-violet light. Buchelos (1980) found a strong response of *N. rufipes* adults in aerial sticky surfaces placed in warehouses with sultanas and Corinth currants.

10. Interspecific competition

Odeyemi (1997) studied the competition between *N. rufipes* and *D. maculatus* in dried fish at different population levels, moisture-content and temperatures. Competition between these two species was found to have an effect on the population growth of both beetles but to different extents. The intensity of competition was directly related to temperature, moisture content and initial density ratio. Using the replacement series approach, it was predicted that at high adult population and moisture content *N. rufipes* becomes extinct and *D. maculatus* dominates. At a temperature of 20 °C, *D. maculatus* reproduces more than *N. rufipes*, while at 32 °C both species co-exist. Consequently, in this competition, *D. maculatus* was the superior competitor. Nevertheless, *N. rufipes* has been found to feed on a wide variety of other insects, even if the prey are present on a non-preferred commodity (Table 3).

11. Forensic status

Zanetti et al. (2015) reported that *N. rufipes* is a scavenger that is capable of producing artifacts in different tissues of pig extremities, as observed under controlled conditions. This species is a late inhabitant of human corpses and feeds on dry cadavers and probably on larvae of other arthropods that share the same environment (Benecke, 1998). Oliva (2001) reported the presence of *N. rufipes* in the corpse of a child in Buenos Aires, Argentina, and found that *N. ruficollis* was more abundant than *N. rufipes*. Souza and Linhares (1997) and Almeida and Mise (2009) recognized *N. rufipes* as having potential forensic importance since it was able to breed in carrion exposed to natural environmental conditions in the vicinity of Campinas city, Southeastern Brazil (Lúcia et al., 2009). Kulshrestha and Satpathy (2001) reported that Dermestidae (known also as skin beetles) and Cleridae (known also as bone beetles) are the most common beetles that infest exposed human remains, and can be used to estimate the minimum postmortem interval.

12. Control and management

Preserved animal products are protected from insect pests, largely by chemical treatments. However non-chemical alternatives, particularly traditional practices, have also been adopted. Multiple pest management options that have been practiced for controlling *N. rufipes* including botanicals (Akinwumi et al., 2007), contact insecticides (Gonzalez, 1957; Walker, 1987), fumigation (Walker, 1987; Nalinakumari and Mammen, 1998) and controlled atmospheres (Odeyemi and Akinnusi, 1985).

12.1. Contact insecticides

Chemical insecticides have been traditionally used in many countries to control *N. rufipes*. Walker (1987) reported satisfactory control of *N. rufipes* in Mali by dipping dried fish in a dilution of 0.02% synergized pyrethrins (1:10 piperonyl butoxide). Guillon (1976) also conducted trials in Mali to control *N. rufipes* infestation of dried fishes, and found that a dip of 1 min in a suspension of tetrachlorvinphos containing 0.0375, 0.075 and 0.1125% active ingredient reduced damage levels by 80, 91 and 93% respectively. Duguet et al. (1985) evaluated the use of dips that contained both

Table 3
Prey of *Necrobia rufipes* and their life stages.

Prey	Life stage eaten	Reference
Piophila casei (L.)	Maggots	Simmons and Ellington (1925)
Dermestes maculatus DeGeer	Eggs, larvae, pupae	Shaumar et al. (1990)
Dermestes frischii Kugelann	Larvae, pupae	Shaumar et al. (1990)
Sarcophaga carnaria (L.)	Pupae	Shaumar et al. (1990)
Parasarcophaga aegyptiaca (Salem)	Pupae	Shaumar et al. (1990)
Wohlfahrtia nuba Wiedemann	Pupae	Shaumar et al. (1990)
Lucilia sericata (Meigen)	Pupae	Shaumar et al. (1990)
Tribolium castaneum (Herbst)	Larvae, pupae	Hasan and Phillips (n.d.)

synergized (1:10 piperonyl butoxide) and non-synergized deltamethrin in Mali. A concentration of 0.0025% of non-synergized deltamethrin gave excellent control of *N. rufipes* for up to 120 days. Roesli et al. (2003) reported that a combination of sanitation and cyfluthrin spray is a reliable control practice for *N. rufipes* management. Golob et al. (1995) tested different insecticides, alone or in combination, and found a good level of fish protection against *N. rufipes* for several weeks after treatment. They treated dried fish by spraying or dipping into liquid solutions of pyrethroid or organophosphorus insecticides, or mixtures containing both. Treated and untreated dried fish were stored for 6 months, during which time they were sampled at regular intervals (12, 16 and 24 weeks) at 25 ± 2 °C and 67 ± 2% r. h., and dead numbers of adults *N. rufipes* were recorded.

Gonzalez (1957) studied the residual effect of benzene hexachloride (BHC), aldrin, methoxchlor, dichloro-diphenyl-trichloroethane (DDT) emulsion, DDT wettable powder, dieldrin emulsion, and dieldrin wettable powder on *N. rufipes*, and found good levels of protection against the pest. Since these insecticides could not be applied directly on copra, especially if it is to be used for human consumption, it was thought advisable to determine the level of protection by applying these insecticides on the surfaces of the storage facility (i.e. floor, walls etc.), with no direct contact with the commodity. The results indicated that all insecticides tested proved to be effective against *N. rufipes* for the first 5 weeks. Nevertheless, after this interval, these insecticides lost their efficacy. In general, surface applications with contact insecticides were found effective for controlling this species, as its adults are often in contact with these treated surfaces. However, treatment with these insecticides would need to take place every 4–5 weeks to maintain control of *N. rufipes*. It was also noticed that when the beetles are disturbed while piling or removing the copra for shipment, the beetles congregate in large numbers on the walls of the warehouse (Gonzalez, 1957).

Mallamaire (1957) conducted research in West Africa and recommended either soaking the materials used to wrap fish with a preparation of 0.6 percent DDT or dusting the outsides of the bales with either 10% DDT or 0.6% gamma hexa-chloro-cyclohexane (HCH) at a rate of 1 mg/m^2 to suppress *N. rufipes* populations. Lloyd and Hewlett (1958) noted that *N. rufipes* was very susceptible when exposed to 0.3% pyrethrins plus 3.0% piperonyl butoxide. Duguet et al. (1985) determined that deltamethrin can be effective for a period of 180 days against *N. rufipes* by dipping 15 kg of gutted fresh fish for 10 min in 10 L of a 0.0025% deltamethrin concentration in water.

Golob et al. (1987) carried out a 6-month trial in Kenya to compare diflubenzuron with pirimiphos-methyl, iodofenphos, fenitrothion and deltamethrin dips to protect dried fish against *D. maculatus* and *N. rufipes*. Pirimiphos-methyl, iodofenphos and fenitrothion were used as aqueous solutions at rates of 0.01% and 0.02% a. i. while deltamethrin was used at 0.001% and 0.002% a. i. All treatments protected the fish against both species throughout the trial period, but diflubenzuron provided a lesser degree of protection than the other compounds. In addition, high residues of diflubenzuron, 26.6 mg/kg after treatment with 0.02% concentrate, were found in the fish 6 months after treatment. These residues were more than 20 times greater than the maximum allowable limit of 1 mg/kg as recommended by the Joint Meeting on Pesticide Residues (JMPR) (Anon, 1982). Diflubenzuron was consequently regarded as an unsuitable application for fish.

12.2. Botanicals

There is a considerable number of studies that have been focused on the evaluation of different types of botanicals for the control of *N. rufipes* (Ward and Golob, 1994; Rajendran and Parveen, 2005; Akinwumi, 2011; Ahmed et al., 2013). Okonkwo and Okoye (2001) reported that the crude seed powders of *Dennettia tripetala* Baker (Magnoliales: Annonaceae) and *Piper guineense* (Schum and Thonn) (Piperales: Piperaceae) inhibited oviposition and achieved complete (100%) adult mortality of *N. rufipes.* Neem, which is produced by the tree *Azadirachta indica* A. Juss. (Sapindales: Meliaceae), has been used traditionally for protecting stored dried fish against *N. rufipes* infestation (Golob and Webley, 1980). Okorie et al. (1990) found that powder made from dried neem seeds applied to dried fish at 2–8% by weight prevented oviposition of *N. rufipes.* Treatment with 2% neem controlled *N. rufipes* larvae. Mathen et al. (1992) reported that neem oil showed some repellent activity against adults of *N. rufipes*. Akinwumi et al. (2007) investigated the effect of natural insecticides obtained from four plant materials, *D. tripetala*, *P. guineense*, *Eugenia aromatic* (L.) (Myrtales: Myrtaceae), and *Monodora myristica* (Gaertn.) Dunal (Magnoliales: Annonaceae) against fish beetles including *N. rufipes* and reported that the absolute ethanol extraction of these plant materials at the concentration of 2.5, 5.0 and 10% could be useful for controlling the mature larvae of *N. rufipes*. They also concluded that these methods could be integrated into insect pest management strategies of fish beetles. Odeyemi et al. (2000) carried out population suppression and toxicity tests against *N. rufipes* using the African locust bean plant *Parkia clappertoniana* Keay (Fabales: Fabaceae) and found that the pod and pulp at the rate of 1.0, 1.5 and 2.0 g for dry powder treatment per 100 g dried fish samples were toxic to larvae and adult *N. rufipes*. They also added that the population of adults generally decreased significantly on treated samples. Okonkwo and Okoye (2001) investigated the insecticidal activity of *D. tripetala* and *P. guineese* against *N. rufipes* and reported that the seed powders and essential oil extracted from these plants significantly inhibited oviposition and achieved 100% adult mortality after 7 days, and there was no progeny development by day 30.

12.3. Fumigation

Though there is limited information available, fumigations are frequently used to control *N. rufipes*, since this species is extremely common in edible commodities such as stored dried fish and dry-cured ham meat, particularly in the USA (Table 4; Cotton and Roark, 1928; Friendship, 1990; Phillips et al., 2008; Sekhon et al., 2009). The earliest reference to fumigation is given by Kimura and Takakura (1919) in Japan, where dried cod was found to be infested by different insect species, including *N. rufipes*. The infested fish was fumigated with carbon bisulphide (carbon disulphide) and hydrocyanic acid gas in store houses, with heating to 60 °C for 1 h reported as the optimum method. Dorokhov (1965) reported that in Russia storage rooms containing fish infested by *N. rufipes* could be fumigated with sulphur dioxide.

Phillips et al. (2008) noted that the eggs of *N. rufipes* were more tolerant to sulfuryl fluoride (SF) than the other life stages. They also mentioned that >20 g/m^3 was required to achieve a complete mortality of all the stages of *N. rufipes* after 48 h of exposure. It was also noted that the adults of *N. rufipes* were more susceptible to SF than the other life stages (Fig. 4).

Nalinakumari et al. (1998) reported that for curative treatment of copra infested by *N. rufipes*, fumigation with aluminium phosphide at 3 g/m^3 for 2 days was required (Fig. 5). According to Rai and Singh (1977) application of aluminum phosphide at 8.1 g/m^3 for 2 days controlled *N. rufipes* that infested copra. It was also reported that application of aluminum phosphide at 0.8 g/m^3 controlled *N. rufipes* in stored cacao beans (Mejule and Onyuike, 1980). Nalinakumari et al. (1998) reported that a dose of 0.85 g/m^3 was found ineffective in copra against *N. rufipes*, the saw-toothed grain beetle, *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae) and the coffee bean weevil *Araecerus fasciculatus* (De Geer) (Coleoptera: Anthribidae). The Fisheries Department of Malawi recommended fumigation of infested dried fish with phosphine under gas-proof sheets at 1.06 g/m^3 for 5 days (Walker, 1983), whereas commercial companies carry out fumigation at dosages ranging from 0.71 to 1.77 g/m^3 over exposure periods of 3–5 days (Friendship, 1990). Walker (1983) carried out a trial of phosphine fumigation at 1.5 g/m^3 and found no live *N. rufipes* after 3 days exposure. Moreover, Hasan et al. (2020) reported that complete mortality of *N. rufipes* was achieved with phosphine treatment of 0.85 g/m^3 for 48 h at 23 °C.

Mallamaire (1957) recommended fumigation with methyl bromide at a dosage rate of 80–100 g/m^3 for the control of *N. rufipes* infestations in dried fish in Senegal and Mali. These fumigations were carried out in a chamber under a partial vacuum. Galichet (1960) observed that methyl bromide at the rate of 80 g/m^3 over exposure periods of up to 23 h at 20–40 °C controlled *N. rufipes* and estimated concentration-time (CT) products of 510 mg-h/l at ≥30 °C and 720-1440 mg-h/l at 20 °C may be needed for efficacy. Kamel et al. (1964) reported that under winter conditions in Egypt, a dose of 24 g of methyl bromide per cubic meter of space for 24 h was effective at controlling all stages of *N. rufipes*. Moreover, Sekhon et al. (2010) recommended that 32 g/m^3 of methyl bromide could be used to fumigate dry cured pork products to control ham beetle infestations. Hasan et al. (2020) demonstrated that a concentration of 4 g/m^3 of methyl bromide at 23 °C for 48 h was sufficient to kill 100% of the exposed *N. rufipes* individuals throughout ontogeny.

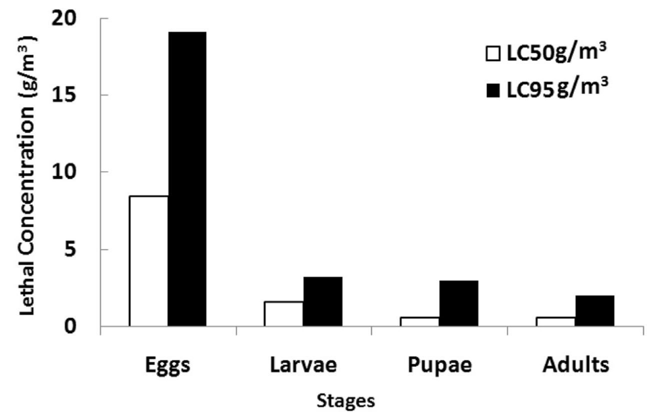

Fig. 4. Lethal concentration estimated to achieve LC_{50} and LC_{95} for sulfuryl fluoride fumigation against *N. rufipes* for 48 h exposure at 23 °C (based on Phillips et al., 2008).

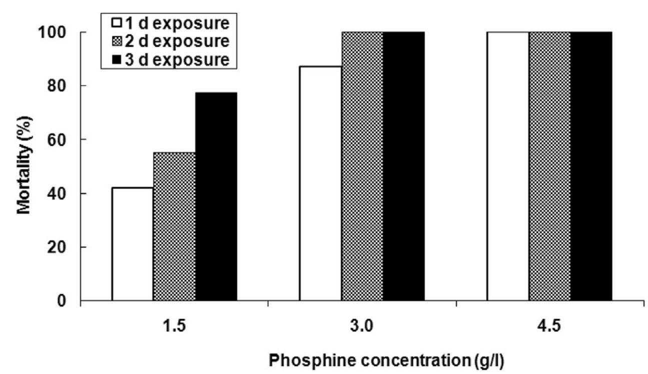

Fig. 5. Mortality (%) of *N. rufipes* adults fumigated with phosphine at varying concentrations and exposures (Based on Nalinakumari et al., 1998).

Table 4
Concentration levels of fumigants required for controlling *N. rufipes*.

Fumigations	Exposure levels	Concentrations	Country used	References
Methyl bromide		80–100 g/m^3	Senegal, Mali	Mallamaire (1957)
	23 h at 20–40 °C	80 g/m^3		Galichet (1960)
	30 °C	CT 510 mg-h/l		Galichet (1960)
	20 °C	CT 720 and 1440 mg-h/l		
	2 days	24 g/m^3	Egypt	Kamel et al. (1964)
	2 days at 23 °C	>7 g/m^3	USA	Hasan et al. (2020)
Phosphine	2 days	3 g/m^3		Nalinakumari et al. (1998)
	2 days	Phostoxin at 8.1 g/m^3		Rai and Singh (1977)
		0.8 g/m^3		Mejule & Onyuike (1980)
	5 days	1.06 g/m^3		
	3–5 days	0.71–1.77 g/m^3	Malawi	Walker (1983)
	3 days	1.5 g/m^3	Malawi	Walker (1983)
	2 days at 23 °C	0.451 g/m^3	USA	Hasan et al. (2020)
Sulfuryl fluoride	2 days at 23 °C	>20 g/m^3	USA	Phillips et al. (2008)

12.4. Controlled atmospheres (CA)

Odeyemi and Akinnusi (1985) investigated the use of nitrogen to control *N. rufipes* and observed that the minimum exposure periods required to achieve 100% mortality in eggs, larvae and adults of this species at 28 °C were 54, 48 and 51 h, respectively. Hasan et al. (2016) reported the feasibility of using controlled atmospheres (CA) for managing *N. rufipes* that infest dry-cured hams, which would also be applicable to these same pests infesting other commodities. Tests were conducted with low oxygen (O_2) achieved with low pressure under a vacuum, and high carbon dioxide (CO_2). Both low O_2 and higher CO_2 levels required exposures up to 144 h to kill 100% of all stages of *N. rufipes*, as well as the cheese mite, *Tyrophagus putrescentiae* (Schrank) (Astigmata: Acaridae) at 23 °C. In addition, both low O_2 and high CO_2 had no significant mortality against both species at short exposures ranging from 12 to 48 h. *Necrobia rufipes* individuals were more tolerant than *T. putrescentiae* to an atmosphere of 75.08% CO_2 and low pressure of 25 mm Hg that imposed an atmosphere of 0.7% O_2. Both low O_2 and high CO_2 trials indicated that the eggs of both species were more tolerant than the other life stages tested, but *N. rufipes* eggs and pupae were more susceptible than larvae and adults to high concentration ozone treatments.

12.5. Irradiation

It has been reported that a 1 kGy dose of ^{60}Co gamma radiation could be sufficient to kill all the stages of *N. rufipes* (Ahmed et al., 1989; Shahjahan et al., 1996). Similar results were also observed by Alam (2004) while working on the effect of gamma radiation against *N. rufipes* throughout ontogeny.

13. Conclusions

There have been numerous research projects conducted on different aspects of controlling *N. rufipes* in the laboratory. It has been shown that morphological characteristics, reproductive potential, development time, and other biological parameters of *N. rufipes* are extremely variable, depending on the specific food source and environmental conditions. Data are lacking for many of the products that are commonly infested by *N. rufipes*, such as cheese, pet food etc. Several studies suggest that populations of *N. rufipes* could be suppressed using residual contact insecticides and fumigation. However, contact insecticides have not been used extensively in the protection of animal origin products. Residue data for these insecticides have not been well documented particularly in developing countries. Further studies are needed to investigate integrated pest management (IPM) tactics for controlling this pest as well as minimizing the insecticidal residues that are frequently deposited in "sensitive" commodities such as meat and cheese. An IPM program for *N. rufipes* would incorporate methods to prevent or slow infestation, techniques to monitor and estimate population increases, and develop action thresholds for effective mitigation, all of which can be addressed in future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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