diversity

MDPI

Communication

Evaluating Formic Acid as a Behavioral Modifier in African Savanna Elephants

Mark G. Wright [1,*], Irene Gatti [2], Michelle G. Au [1], Juliana Salehi [1], Craig R. Spencer [2], Paul Allin [2] and Agenor Mafra-Neto [3]

1 Department of Plant and Environmental Protection Sciences, University of Hawai'i at Mānoa, 3050 Maile Way, Honolulu, HI 96822, USA
2 Transfrontier Africa, Olifants West Nature Reserve, Hoedspruit 1380, South Africa
3 ISCA Inc., 1230 Spring Street, Riverside, CA 92507, USA
* Correspondence: markwrig@hawaii.edu

Abstract: Formic acid was investigated as a potential repellant for African savanna elephants (*Loxodonta africana*) as a semiochemical option for managing elephant movements and interactions with human infrastructure. Formic acid is a naturally occurring compound, used as an alarm pheromone and as a defensive chemical in Formicine ants, and thus a potentially desirable option compared to introducing exogenous deterrents that are foreign to the elephants' natural habitats. Although most elephants observed (85%) did not interact with treatments containing formic acid, of the cohort of individuals (n = 38) that did respond, the majority showed a mild to moderate avoidance response, while a small proportion of elephants were distinctly repelled when experiencing formic acid cues, in some cases causing whole herds to evacuate an area. The potential for using formic acid as an elephant repellant to modulate elephant behavior in field situations is discussed.

Keywords: human-elephant conflict; behavior modification; olfactory cue

check for updates

Citation: Wright, M.G.; Gatti, I.; Au, M.G.; Salehi, J.; Spencer, C.R.; Allin, P.; Mafra-Neto, A. Evaluating Formic Acid as a Behavioral Modifier in African Savanna Elephants. *Diversity* **2023**, *15*, 1079. https://doi.org/10.3390/d15101079

Academic Editors: Michelle Henley and Michael Wink

Received: 22 August 2023
Revised: 2 October 2023
Accepted: 9 October 2023
Published: 12 October 2023

1. Introduction

Elephants require extensive land areas to fulfill their ecological needs. Human population growth and correlated increased impacts on natural areas result in increased human–wildlife conflicts [1,2]. Globally, elephants become entangled in human–elephant conflict situations, including damage to crops on subsistence and commercial farms, impacts on infrastructure such as roads and water supply pipes, destruction of large established trees in conservation areas, and endangering people on farms. Numerous options for containing elephants, particularly the African bush elephant, *Loxodonta africana*, within conservation areas, or managing their behavior outside of them, have been developed or are being investigated. These options include physical boundaries and a diversity of potential deterrents, such as noxious-smelling plant extracts, sound, honey bee hive fences, and synthetic honey bee alarm pheromone blends [3–8]. These alternatives all have some level of success but are not completely effective as stand-alone measures to manage elephant movements. Developing an integrated suite of options for elephant movement management likely provides the best option for sustainable solutions. This is particularly relevant as elephants habituate quickly to artificial deterrents and human–elephant conflict amelioration tactics in general [7,9,10]. Elephants, when subjected to painful encounters with social insects such as honey bees and ants, can associate these negative experiences with related cues, conditioning them to exhibit avoidance behaviors. Elephants have highly developed olfactory abilities [11,12], and the use of olfactory warning cues may provide a viable addition to the tools available for elephant deterrence.

Previous work in Kenya has demonstrated that elephants are repelled by ants (*Crematogaster* spp., Formicidae) that inhabit the large galls they produce on *Vachellia* (previously *Acacia*) trees [13,14]. When disturbed by herbivore feeding activity, the ants leave the galls and release chemical signals or swarm the herbivore, inflicting bites and stings [15]. The elephants are likely deterred by olfactory cues from the ants to avoid future stinging or biting on sensitive parts of their faces. Elephants are deterred by honey bees (*Apis mellifera*, Apidae) as they are sensitive to stings around their eyes, ears, and in their trunks, which is the foundation for success in deterring elephants with living honey bee hive fences. When threatened, hive guard honey bees release alarm pheromones, blends of organic compounds, that result in the disturbed colony launching a mass attack on the animal that is agitating the hive. It has been demonstrated that elephants are deterred by a synthetic blend of compounds within the bee alarm pheromone blend when deployed in the environment [8].

Some tree species in South Africa harbor various aggressive ant species using the tree as a foraging substrate or in wounds caused by elephant feeding activities, nesting them within the tree bark. While these examples are a less intimate tree–ant association than gall-forming ants in Kenyan *Acacia* trees [16], the frequent presence of ants in trees may provide a form of defense against further damage by elephants, as they may respond to the disturbances by biting, releasing attack pheromones, or formic (methanoic) acid towards the elephants. Formic acid is produced by ant species in the subfamily Formicinae as a defensive chemical [17,18]. Formic acid is a volatile substance with a pungent smell, is a respiratory irritant, and can cause minor skin burns at high concentrations [19].

Based on preliminary observations of formicine ants occurring on marula trees (*Sclerocarya birrea*, Anacardiaceae, a preferred food source for *L. africana*) and possibly reduced elephant damage on trees with ants [20], we tested the hypothesis that elephants would be deterred by exposure to formic acid. Formicine ants observed on trees in the study area (see below) included *Camponotus* sp. and *Anoplolepis* sp., which are known to use formic acid in their defensive attacks. We describe the reaction of elephants exposed to a formic acid formulation as a potential deterrent to elephants impacting trees.

2. Materials and Methods

This work was conducted in the Olifants West Nature Reserve (OWNR, 24°214′ S, 30°858′ E), a private nature reserve associated with the Greater Kruger Park, South Africa. OWNR has large numbers of elephants at certain times of the year, and large herds are often observed feeding and visiting water holes. While in the area, elephants frequently cause impacts on infrastructure and feed on large trees, marula trees in particular.

To test whether the semiochemical formic acid may result in elephant repellence, we formulated 20% formic acid (v/v) in SPLAT® (Specialized Pheromone and Lure Application Technology, ISCA Technologies, Riverside, CA, USA) and then deployed and tested the formulation at waterholes in the OWNR as described previously by Wright et al. (2018) [8] for experiments with a synthetic honey bee alarm pheromone blend, also formulated in SPLAT. The SPLAT formulation without the semiochemical served as the untreated control. The formic acid formulation and control treatments were deployed at waterholes between 08:00 and 15:00 h, placing 20–25 g of each formulation treatment into white socks, weighted with a small rock, and suspended from branches around the waterholes [8]. Waterholes were chosen as the experimental sites to increase the likelihood of elephant visits to a predictable location rather than to determine whether the formic acid would deter them from a desired resource. Elephant responses to the treatments were video recorded by observers, and their behaviors were analyzed to determine if they included repellency or deterrence responses. Responses were categorized on a numeric ordinal scale as follows: 0 = no response or 'curiosity' to the treatments and no signal of deterrence or stress behavior; 1 = mild 'concern', displaying foot-waving and slight trunk elevation behaviors; 2 = distinct 'concern' or repellence, involving behaviors such as ear-flapping, elevated trunk, erect tail, trumpeting, and direction change; and 3 = dramatic response, where the individual moves away rapidly or the entire herd departs in response to an individual's reaction. Herd size, sex, and approximate age of individuals interacting with the treatments were documented. Ranked response data were analyzed using the JMP Pro 17 [21] ordinal logistic regression fit procedure or generalized linear models (with the Firth adjusted maximum likelihood estimation method) for binomial data [21]. Proportions of individuals reacting by sex were analyzed using a two-way contingency table (Fisher's exact test) in JMP Pro 17.

3. Results

The elephants that arrived at waterholes typically approached the water at a rapid walking pace. Single males or small bachelor herds often seemed more conscious of their surroundings and appeared to notice the test treatments more frequently than animals in breeding herds. The elephants approaching the water hole would frequently drink before moving away from the water, when they would encounter the socks. When large breeding herds were present, they would frequently drink and subsequently mill around in the area close to the waterhole, often only encountering the test treatments after drinking.

Elephants encountering the formic acid treatments had a range of responses summarized in Table 1. Mild responses included the individual stopping abruptly at the treatment, with the trunk slightly raised and a foot swaying. Those individuals showing distinct signs of deterrence would elevate their trunk, flap their ears vigorously, and move away from the treatment, often changing direction in the process (see Supplementary Materials Video S1). On one occasion, a small herd of five individuals was observed to be repelled after a young cow (10–15-year-old subadult) detected the formic acid treatment and demonstrated uncertainty through foot-waving, followed by stiffened ears and a raised tail. As the young cow responding to the treatment changed direction and showed distinct startled body posturing, all members of the herd rapidly departed the waterhole (not included in statistical analyses) (see Supplementary Materials Video S2). Twenty-six elephants interacted with the controls; of these interactions, 21 were scored 0, and five were scored 1. Of the 21, 11 elephants simply sniffed the controls and moved past; one tried to dislodge the control; nine showed no reaction. Of the five that scored a 1, all showed signs of slight distress.

Table 1. Summary of elephant responses to formic acid treatments from video recordings. An additional eight records * had no video and were transcribed from notes. Response ratings are as described in methods.

Herd Size	Demographic of Responding Animal	Response Rating	Behavior
5	Subadult male	3	Strong reaction, whole herd leaves waterhole (Video S2)
3	Subadult male	0	Curious about socks
1	Adult male	1	Foot and trunk wave
6	Subadult male	3	Trunk raised, retreated quickly (Video S1)
6	Subadult male	0	Curious about socks
6	Subadult male	1	Foot wave
6	Subadult male	1	Foot wave
2	Adult males	1	Foot wave; threw sock
9	Calf	2	Ran away from sock
1	Adult male	2	Backed away, avoided sock
1	Adult male	1	Foot wave
8	Subadult female	1	Backed away
8	Subadult female	1	Backed away, foot wave
21	Adult female	1	Foot wave, backed up
21	Subadult male	1	Head shake, backed up
16	Subadult male	2	Backed away rapidly
1	Adult male	1	Foot wave
14	Adult female	1	Foot wave
15	Subadult male	2	Head toss, turned away from sock
15	Matriarch	1	Foot wave
15	Subadult male	1	Threw sock

Table 1. *Cont.*

Herd Size	Demographic of Responding Animal	Response Rating	Behavior
14	Calf	0	Curious
14	Subadult male	1	Threw sock
3	Subadult female	0	Distracted by other elephants as detecting sock
1	Adult male	1	Paused approaching sock
1	Adult male	1	Foot wave
1	Adult male	1	Pause, slight retreat
8	Subadult male	1	Foot wave, slight retreat
6	Subadult female	0	Curious
14	Subadult male	2	Foot wave, head toss, turned away

* Records from notes lacking full data. Reactions to formic acid: rating 1, $n = 2$; rating 2, $n = 3$; rating 3, $n = 2$.

Of the 261 elephants that visited the waterholes during the experiments, 38 individuals interacted with the treatments. When encountering formic acid treatments, the elephants showed significantly heightened responses compared to the control treatments they interacted with (ordinal logistic regression: $\chi^2 = 10.18$; d.f. = 1; $p = 0.0014$). Of these responding elephants, three groups and some individuals had a dramatic response, whereas five showed distinct, heightened signs of concern, and 18 showed mild concern in response to the formic acid. In some cases, the elephants would attempt to dislodge the formic acid treatment from the branch by attempting to push over the supporting branches, sometimes backing up and kicking at the branch with their rear feet as if provoked by its presence. Herds with five or more individuals were more likely to include individuals that reacted to the formic acid treatment (GLM: $\chi^2 = 6.66$; d.f. = 1; $p = 0.0098$). Although 69% of individuals interacting with the treatments were bulls, there was no effect of age demographic (GLM: $\chi^2 = 8.71$; d.f. = 7; $p = 0.274$) or sex (Fisher's exact test, $p = 0.689$) on the probability of an elephant's response to formic acid.

4. Discussion

The experimental data showed that the elephants that interacted with the formic acid treatments had a significantly greater deterrence response, albeit generally mild, than those that interacted with the control treatments, similar to the behavioral signs of concern and repellency observed in previous testing when elephants encountered formulations containing synthetic honey bee alarm pheromones [8]. However, most elephants simply ignored the formic acid treatments, even when passing close to them. The lack of response of these elephants may be due to several issues, including the result of minimal or lack of previous negative experiences with ants in the field or simply because the elephants were walking upwind from the odor. Elephants that have not experienced strong negative ant interactions are unlikely to learn to avoid ants and their associated cues. It is likely that the majority of the elephants in OWNR were naïve to negative interactions with ants, and this is likely reflected in the low number of individuals showing any response to the formic acid treatments during our experiments. While formic acid may have some potential to repel elephants, its application may be limited by the frequency at which elephants encounter ants in their environment. However, the behaviors observed in elephants that responded to the formic acid treatment do express the typical alarm response and deterrence, similar to those reported in other studies where elephants are exposed to potential threat signals such as recorded sounds of agitated bees [7] or synthetic honey bee alarm pheromones [8]. To humans, formic acid has a pungent odor. It is also possible, therefore, that individual elephants simply find formic acid disagreeable. However, the fact that some showed distinct signs of concern and deterrence behavior suggests that these responding elephants may have had an unpleasant experience with ants, and the formic acid odor might trigger the expectation of another negative exposure to an organism that could cause them pain. The herd avoidance response illustrated in this paper is consistent with situations where an individual elephant provides a warning of impending or potential danger to others, resulting in collective responses by the entire herd [22,23].

An alternative scenario to elephants encountering aggressive formicine ants on trees is that they disturb ants on the ground and invoke an emission of alarm pheromones and a mild defensive response. These elephants might become habituated to formic acid or simply not associate it with a deterrent cue. However, formicine ants can be abundant on the ground in African savanna, and while no observations have been made to suggest that elephants avoid them, it is plausible that elephants walking over aggressive formicine ant nests may be attacked by swarms of these ants secreting defensive chemicals such as formic acid and thus learn to avoid them and their odor cues. Direct observation of elephants moving through landscapes with high formicine ant nest density could show whether this is the case. It may also be possible to assess whether elephant activity is low in areas with high formicine ant activity using data from collared elephants that are tracked over long periods.

It may also be worth considering experiments to condition elephants to avoid formic acid through classical conditioning. For example, placing formic acid on or near active beehives intended for elephant deterrence would likely result in the elephants developing a negative association with bees, now with a stronger compounded olfactory cue from the formic acid and honey bee alarm pheromones. Asian elephants, for example, have been shown to quickly learn and remember to associate atypical odors with rewards [24] and could certainly be conditioned to avoid specific odors. While formic acid is typically present in small quantities in honey bee hives, a high dose of this chemical protects against parasitic varroa mites (*Varroa destructor*) while being harmless to honey bees (e.g., formic acid fumigation for varroa mite management in beehives [25]), with the advantage that it does not elicit an attack response from the bees, as an alarm pheromone would. Formic acid could also be deployed with other technologies, such as drones, to condition elephants to associate its odor with other typically mechanical and sound-repellent stimuli.

While this paper reports a limited number of interactions between elephants and formic acid treatments, we were able to detect distinct deterrence in a number of interactions and heightened alarm responses in other cases. This suggests that formic acid may be worth considering as an additional semiochemical option for inclusion in integrated elephant deterrence procedures. Formic acid is a naturally occurring and volatile compound that does not have any negative, toxic, or persistent qualities when deployed in the environment. Further investigation of formic acid as a deterrent to which elephants may be conditioned should be considered.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/d15101079/s1: Video S1, individual elephant shows distinct deterrence (response rating 3) from formic acid at 42 s (video: Linda Crawford); Video S2, dramatic response of herd reaction to formic acid treatment, starts at 20 s (video: Irene Gatti).

Author Contributions: Conceptualization: M.G.W., C.R.S., P.A. and A.M.-N.; Data collection and analyses: M.G.A., I.G. and J.S.; origin draft: M.G.W. All authors: review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: The Eva Crane Trust (UK) is thanked for providing funding that permitted this work to be carried out.

Institutional Review Board Statement: UH IACUC Protocol 17-2561-4-6 was approved by the University of Hawaii Animal Care & Use Committee.

Data Availability Statement: Field data will be supplied upon request.

Acknowledgments: Landowners in the OWNR are thanked for permitting access to study sites for this work. Linda Crawford and many other Transfontier Africa volunteers assisted with data collection.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ngama, S.; Korte, L.; Bindelle, J.; Vermeulen, C.; Poulsen, J.R. How bees deter elephants: Beehive trials with forest elephants (*Loxodonta africana cyclotis*) in Gabon. *PLoS ONE* **2016**, *11*, e0155690. [CrossRef]
2. Cook, R.M.; Witkowski, E.T.F.; Helm, C.V.; Henley, M.D.; Parrini, F. Recent exposure to African elephants after a century of exclusion: Rapid accumulation of marula tree impact and mortality, and poor regeneration. *For. Ecol. Manag.* **2017**, *401*, 107–116. [CrossRef]
3. Cook, R.M.; Witkowski, E.T.F.; Henley, M.D. Survival trends (2008–2020) of three tree species in response to elephant impact, environmental variation, and stem wire-netting protection in an African savanna. *For. Ecol. Manag.* **2023**, *54*, 121220. [CrossRef]
4. Dampage, U.; Thajudeen, R.; Jasenthuliyana, S.; Jayawardena, J. Automated virtual elephant fence based on detection, alarming, and coordinated redirection of wild elephants. *Environ. Monit. Assess.* **2021**, *193*, 240. [CrossRef] [PubMed]
5. Henley, M.D.; Cook, R.M.; Bedetti, A.; Wilmot, J.; Roode, A.; Pereira, C.L.; Almeida, J.; Alverca, A. A phased approach to increase human tolerance in elephant corridors to link protected areas in southern Mozambique. *Diversity* **2023**, *15*, 85. [CrossRef]
6. King, L.E.; Lala, F.; Nzumu, H.; Mwambingu, E.; Douglas-Hamilton, I. Beehive fences as a multidimensional conflict-mitigation tool for farmers coexisting with elephants. *Conserv. Biol.* **2017**, *31*, 743–752. [CrossRef] [PubMed]
7. King, L.; Pardo, M.; Weerathunga, S.; Kumara, T.V.; Jayasena, N.; Soltis, J.; de Silva, S. Wild Sri Lankan elephants retreat from the sound of disturbed Asian honey bees. *Curr. Biol.* **2018**, *28*, R64–R65. [CrossRef]
8. Wright, M.G.; Spencer, C.R.; Cook, R.M.; Henley, M.D.; North, W.; Mafra-Neto, A. African bush elephants response to a honeybee alarm semiochemical blend. *Curr. Biol.* **2018**, *28*, R778–R780. [CrossRef]
9. Goodyear, S.E.; Schulte, B.A. Habituation to auditory stimuli by captive African elephants (*Loxodonta africana*). *Anim. Behav. Cogn.* **2015**, *2*, 292–312. [CrossRef]
10. Valenta, K.; Schmitt, M.H.; Ayasse, M.; Nevo, O. The sensory ecology of fear: African elephants show aversion to olfactory predator signals. *Conserv. Sci. Pract.* **2020**, *3*, e333. [CrossRef]
11. Greenwood, D.R.; Comeskey, D.; Hunt, M.B.; Rasmussen, L.E. Chemical communication: Chirality in elephant pheromones. *Nature* **2005**, *438*, 1097–1098. [CrossRef]
12. Plotnik, J.M.; Shaw, R.C.; Brubaker, D.L.; Tiller, L.N.; Clayton, N.S. Thinking with their trunks: Elephants use smell but not sound to locate food and exclude nonrewarding alternatives. *Anim. Behav.* **2014**, *8*, 91–98. [CrossRef]
13. Goheen, J.R.; Palmer, T.M. Defensive plant-ants stabilize megaherbivore-driven landscape change in an African savanna. *Curr. Biol.* **2010**, *20*, 1768–1772. [CrossRef] [PubMed]
14. Palmer, T.M.; Brody, A.L. Enough is enough: The effects of symbiotic and abundance of herbivory, growth, and reproduction in an African acacia. *Ecology* **2013**, *94*, 683–691. [CrossRef]
15. Hays, B.R.; Riginos, C.; Palmer, T.M.; Doak, D.F.; Gituku, B.C.; Maiyo, N.J.; Mutisya, S.; Musila, S.; Goheen, J.R. Demographic consequences of mutualism disruption: Browsing and big-headed ant invasion drive acacia population declines. *Ecology* **2022**, *103*, e3655. [CrossRef] [PubMed]
16. Hölldobler, B.; Wilson, E.O. *The Ants*; Harvard University Press: Cambridge, UK, 1990. [CrossRef]
17. Eisner, T.; Baldwin, I.T.; Conner, J. Defense-mechanisms of arthropods. 120. Circumvention of prey defense by a predator—Ant lion vs. ant. *Proc. Natl. Acad. Sci. USA* **1993**, *90*, 6716–6720. [CrossRef] [PubMed]
18. Touchard, A.; Aili, S.R.; Fox, E.G.P.; Escoubas, P.; Orivel, J.; Nicholson, G.M.; Dejean, A. The biochemical toxin arsenal from ant venoms. *Toxins* **2016**, *8*, 30. [CrossRef] [PubMed]
19. Sigma-Aldrich. *Formic Acid Material Safety Data Sheet*; Sigma-Aldrich: St. Louis, MO, USA, 2023; Available online: https://www.sigmaaldrich.com/US/en/sds/sigald/f0507 (accessed on 4 August 2023).
20. Wright, M.G.; Au, M.G.; Salehi, J. *Preliminary Field Observations on Elephant Feeding Related to Ant Presence on Marula Trees in the Olifants West Nature Reserve*; University of Hawaii: Hawaii, HI, USA, 2023; Unpublished Data.
21. *JMP® Pro 17*, SAS Institute Inc.: Cary, NC, USA, 1989–2023.
22. O'Connell-Rodwell, C.E.; Wood, J.D.; Rodwell, T.C.; Puria, S.; Partan, S.R.; Keefe, R.; Shriver, D.; Arnason, B.T.; Hart, L.A. Wild elephant (*Loxodonta africana*) breeding herds respond to artificially transmitted seismic stimuli. *Behav. Ecol. Sociobiol.* **2006**, *59*, 842–850. [CrossRef]
23. O'Connell-Rodwell, C.E.; Wood, J.D.; Kinzley, C.; Rodwell, T.C.; Poole, J.H.; Puria, S. Wild African elephants (*Loxodonta africana*) discriminate between familiar and unfamiliar conspecific seismic alarm calls. *J. Acoust. Soc. Am.* **2007**, *122*, 823–830. [CrossRef]
24. Arvidsson, J.; Amundin, M.; Laska, M. Successful acquisition of an olfactory discrimination test by Asian elephants. *Elephas maximus. Physiol. Behav.* **2012**, *105*, 809–814. [CrossRef]
25. VanEngelsdorp, D.; Underwood, R.M.; Cox-Foster, D.L. Short-term fumigation of honey bee (Hymenoptera: Apidae) colonies with formic acid and acetic acids for the control of *Varroa destructor* (Acari: Varroidae). *J. Econ. Entomol.* **2008**, *101*, 256–264. [CrossRef] [PubMed]