First Peoples and scientists concur that ‘fairy circles’ are termite *linyji*

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Abstract

Scientists aspire to 'discover' new environmental phenomena; they rarely consider the existing knowledge of First Peoples. The scientific debate1 over 'fairy circles' (regular bare patches within arid grasslands) is a case in point. Ecologists visiting Australia used brief field observations and numerical modelling to explain 'fairy circles' as plants responding to dispersion of water and nutrients2,3. By contrast, Australian Aboriginal people have long understood the bare patches to be created by termites. They have used linyji (Manyjilyjarra language) in their food economies and for other domestic or sacred purposes. They transfer intergenerational knowledge of termite ecology through talk and demonstration, art and song. Aboriginal art and narratives, and scientific field measurements confirm Aboriginal knowledge that 'fairy circles' are pavement-nests occupied by harvester termites. Aboriginal people's observations and uses of termites and pavements are sophisticated; linyji are real, 'fairy circles' are not. Some scientists are not familiar with First Peoples or their knowledge systems. However, embracing First Peoples and their knowledge can provide a deeper understanding of ecological systems than is possible from short visits to landscapes. Co-research between First Peoples and scientists leads to better understanding and management of ecological systems and supports intergenerational learning across diverse cultures.

Full Text

Visiting scientists ignore First Peoples' knowledge

For centuries, scientists have aspired to make significant discoveries in distant lands, following Humboldt, Wallace and Darwin. They devise explanations for phenomena in the best traditions of their own society, culture and knowledge. However, they do research over short periods of time (sometimes just days) without seasonal or longer-term perspectives, and their neo-colonist explanations may have little local relevance or application[4].

In comparison, First Peoples have experienced their local environments over millennia (see Supplementary Table S1 for terminology). Their knowledge is complex, incorporating variation over seasons and centuries, to support local demands for food, medicines, clothing, and shelter. Yet visiting scientists rarely engage with First Peoples and often ignore their knowledge.

Published scientific explanations, even if incorrect, can persist and become orthodoxy, while First Peoples knowledge and local knowledge fades under colonial and modern pressures[5]. Australian 'fairy circles' are a recent example of this problem. Visiting scientists 'discovered' patterns of bare patches of soil in spinifex grasslands of arid Australia, then expanded theoretically elegant explanations from Africa to Australia without testing their observations or explanations against the ecological knowledge of Australian Aboriginal people.

Scientists have debated causes of so-called 'fairy circle' patterns in arid Namibia and Angola since the 1970s [6,1] (see 1 for review). The observed circles are 2-24 m diameter bare patches within grassy vegetation. 'Fairy circle' origins have variously been attributed to eroded termite mounds, bacterial and fungal populations, *Euphorbia* toxins[7], insects (mostly termites[8]), plant self-organisation, or plant – termites interactions[1]. Continuing the long tradition of scientific colonisation, these scientists have not reported on the knowledge of African San or other Peoples. In 2016, the plant-only hypothesis was extended to 'hexagonal spots' observed in desert grassland in north-western Australia[2,3,9,10]. The work made no reference to Australian Aboriginal knowledge about these phenomena. Researchers concluded that the spots were created by grasses self-organising while competing for water and nutrients.

The plant self-organisation theory is inconsistent with knowledge shared by Martu people with us. Martu people are clear that the bare circular areas are formed and occupied by termites, as also reported by other Australian ecologists[11,12]. Our non-Indigenous authors are also familiar with the ecology of termites, subterranean termitaria and termite pavements from decades of desert walking and observation.

Getzin and colleagues sampled soils to 5cm[2] and later 20 cm[9]. They found little termite activity (determined only as termite mounds and foraging holes) and concluded there was no correlation between termite activity and the 'hexagonal spots'. Their 'discovery' was amplified by Australian and international press[13]. After our alternative understanding[14] was contested[15], we further explored First Peoples' art and knowledge (Figure 1, Extended data table), identified the pan-continental and regional distribution of the spot patterns and pavements (Figure 2a, b), then surveyed the same plots excavated by Getzin and colleagues[2,3,9] (Figure 2c, Figure 3).

Deep-time Indigenous knowledge of termite-rich desert ecosystems

Arid ecosystems are highly variable in space and time. Scientists frequently describe Australian desert systems as 'unpredictable'[18] because modern studies rarely have the longevity to see long-term patterns. Studies in desert systems are often too temporally short, too spatially small, or too Eurocentric to accurately interpret the variability and subtlety of these vast, ancient ecosystems. In contrast, Indigenous people have lived continuously in Australian deserts for at least 50,000 years[19]. Their knowledge of ecosystem function has been adapted and transmitted over more than two-thousand generations of people.

As in all hot deserts, termites are one of the few herbivores able to digest cellulose. Termites thus form a primary link in desert food webs[20]. This includes Australian deserts dominated by spinifex grasses (*Triodia* spp) where many vertebrates are reliant on termites for food[18]. Termites are the 'krill of the deserts'.

The roles of termites in desert peoples' lives deserves systematic study. Most non-Indigenous people consider termites to be pests, while First Peoples see them as beneficial[21]. With some exceptions[22], termites have been overlooked or misnamed by ethnographers writing about Australian Indigenous cultures (e.g. art documentation commonly calls them 'flying ants'). Consequently, international reviews of edible and medicinal termite use by First Peoples omit Australian Indigenous uses[23].

Our evidence shows that termites have been, and continue to be, profoundly important to desert Aboriginal people. In arid regions, harvester termite pavements, mounds, winged termites, other termite castes and termite soils have been intensively used for both secular and sacred purposes. Fifteen desert nations and language groups have lexicons related to termites (Figure S2). We documented thirty-eight uses of harvester termites and their pavements by desert Aboriginal people (Table S2, Figure S3a-f). These records span continental Australia, and we assume there are more to be found.

Near the area previously investigated by Getzin et al. (2016), Manyjilyjarra speakers stated that *yiwany* (termites) lived under the *linyji* (pavements). They classified at least four taxa of flying termites including those flying from *linyji* (Table S2; Figure S4). These alates are seasonally abundant, oil-rich, eaten by animals, and classed as gourmet food (*wama*) by Martu and their neighbours. Pre-emergent alates and winged alates were abundant in episodic flushes, when "bucketsful" were collected by people to eat (Kirriwirri, pers. comm. 22/5/1986; see extended data table). Pintupi, Warlpiri and other people say that flying termite abundance corresponds with high rainfall periods and contributes to both game animal and human condition or 'fatness'[24,25]. In the past, people magnified these benefits through increase ceremonies which is believed to have led to periods of higher human fecundity[24] (Table S2).

Seeds provided the bulk of food in Australian desert economies[26,27], and were threshed by hand on the surface of termite pavements or by foot in pits excavated into pavements[28] (Figure 1c, Figure S3, Table S2). Whilst archaeologists and ethnographers study the use of seed-grinding stones[29], the vital threshing stage is poorly described. The use of termite pavements, hand stones and pivot poles to thresh bulk quantities of seed warrants attention.

Aboriginal people integrate body and ground paintings, sculptures and stories, dances and songs to encode accumulated ecological understandings[24]. These media are embodied in ceremonies and narratives which help sustain knowledge during periods when species are absent or invisible (being underground) during periods of low rainfall[29]. Contemporary Aboriginal art continues to record such termite ecological knowledge. We found 73 artworks related to pavement termites, painted by 34 desert artists who associate with 'Dreamings' for flying termites (i.e., alates) and their pavements (see Supplementary Table S1 for terminology). These artists portray the habits of harvester termites, including the spatial patterning of pavements in grasslands (Figure 1b), along with deeper layered cultural meanings. Western ecologists have been blind to ecological information encoded in Australian Indigenous art and its narratives.

Desert Aboriginal people, including Warlpiri and Anmatyerr, conducted flying termite ceremonies to sustain and promote people-termite relations and productivity[24]. Ceremonial dances by Pitjantjatjara women to increase seed-food production replicated the foot movements of seed threshing in pits dug into termite pavements (Figure 1c). Similar rituals were probably performed by other desert groups.

Aboriginal art also shows that burn mosaics in grasses occurred amongst pavement patterns (Figure 1b; Figure S5a). The burning practices of Aboriginal people were critical to create and maintain diverse seral stages of perennial spinifex grasslands[27]. Burning promotes a diversity of food types that were threshed in or on pavements (Table S2). Pavements in grasslands allowed desert women to unlock the energy and nutrients contained in the grasses that dominated their landscapes. Thus, the interactions between termite pavements, grasses, burning and food processing helped supply the carbohydrates needed to nourish desert human populations who expanded in the mid to late Holocene[30].

We observed eroded pavements in Mulga (*Acacia aneura, sensu lato*) shrublands beyond the margins of the relatively stable sandplain landform (Figure S4d, e). These shrublands have developed along water courses that are slowly eroding into landforms containing pavements, suggesting that the Pilbara termite pavement structures may have great antiquity, possibly from the Pleistocene. Earthen termite nests in arid landscapes are known to persist for thousands of years after their inhabitants have died[31]. Indigenous beliefs perceive human-ecological systems as tightly interconnected[32]. There may have been connections between old sandplain pavement landforms, Aboriginal burning practices, and the response of termites to those practices. These could have co-evolved through ecologically transformative land-use practices[33].

Comparing Indigenous and western scientific understanding of termite ecology

To corroborate Aboriginal knowledge and art, we applied standard scientific methods to re-survey the 'fairy circles' plots (Figure 2c; Figure 3a-c) previously reported[3,9]. Our hand excavations to 15 cm revealed termite chambers throughout the trenches. The 24 pavements excavated consisted of dense consolidated soils incorporating termite chambers (Figure 3b, c). After cleaning, these excavations revealed chambers filled with termite chaff or dark termite frass (Figure 3c), or were open, with some showing black wall-lining (possibly fungal mycelia). Grass harvester termites (*Drepanotermes perniger*) were found in 41% of the trenches (Figure 4).

The consolidated soil material within all pavements was dense and difficult to excavate by hand, while the spinifex sandplain soil between pavements was soft, friable and easily dug to 65 cm depth without any signs of consolidation. Termite foraging tunnels were found in the surface soils (0-5 cm) of the inter-pavement grasslands (Figure 4), with radial surface foraging tunnels originating from nearby pavements[34]. Termites had cut and transported short sections of dry *Triodia basedowii* stems into chambers within the pavements (Figure S4c).

As indicated by Aboriginal art and narratives, we found pavement surfaces function as ephemeral reservoirs of rainwater; the pavement surfaces were 2-3 cm lower than adjacent spinifex sandplain surfaces. Rainwater infiltrated the consolidated subsoils more slowly than in the adjacent sandplain (Figure 3d). A thin (<2 mm) spongy layer was observed on pavement surfaces; similar material in arid zone salt lakes has been attributed to microbial activity promoted by alternating dry-wet conditions[35]. Our field observations concur with Aboriginal people's use of *linyji* as short-term sources of drinking water that were vital to people and other animals in extremely arid ecosystems. Aboriginal knowledge and the field results both support the role of termites as crucial in the creation of bare patches. There are questions to be explored about the interactions between termites, soil, water and plants and the relative magnitude of these interactions[36].

Co-learning and research across generations and cultures helps sustain deep-time knowledge and enriches science

Substantial international research into 'fairy circles' has not reported on First Peoples' knowledge; our work begins to remedy this failure. As in other countries, neo-colonial "helicopter research"[37] that ignores Indigenous people is common in Australia. Short-term visiting scientists can make flawed interpretations of Australian and other desert systems. These misinterpretations are perpetuated through citations[38] and by public media. Incorrect information further undermines Indigenous people's knowledge and contributes to mismanagement of desert ecosystems.

World-wide, First Peoples' languages and detailed ecological knowledge are threatened by rapid ecosystem and economic changes[39]. Many First Peoples demand that younger generations learn about the cultures and Laws of their Country, and be supported to do so[40]. The urgency to strengthen traditional knowledge partly stems from its potential to support social and ecological resilience and help respond to current and future global changes[5].

The co-development of partnerships with First Peoples knowledge holders can support priorities of both First Peoples and scientists. First People benefit from participation and intergenerational knowledge transfer, scientists benefit from challenges to theories and catalysts for new hypotheses. However, the challenges and compromises required are substantial[41]; in particular, scientists need to recognise colonial impacts and improve on the inequities of neo-colonialism.

To understand more about people-termite-grassland dynamics and ecology, collaborations between First Peoples, researchers and land managers are crucial. Actions include listening to each other, learning the knowledge offered, and sharing (e.g., Figure S6). Our continued weaving together of First Peoples' knowledge, local knowledge, and scientific knowledge, demands a collaborative approach where we deepen trust and understanding. The principles and processes for such partnerships are well established, if less well adhered to[5,42-44]. The knowledge of First Peoples is critical to safeguarding the biological and cultural diversity of our planet[45].

Declarations

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Author contributions

Foundational knowledge is from Martu elders and traditional knowledge experts. F.W. and P.K. conceived and led the project. Data were collected by F.W. and P.K. in the Pilbara, and D.M., J.S. and F.W. at Newhaven. Ethnographic data were collected and collated by F.W. Photographs are by F.W except where otherwise credited. Field data were analysed and visualized by F.W., P.K. and A.S. Termite identifications by T.E. Artworks sourced by F.W. and M.N and catalogued by M.N. Maps by M.N. Manuscript drafted by F.W. and P.K. with substantial contributions from A.S., C.O., D.M., J.S., M.N. and T.E. Each individual author edited and proofread the paper.

Data availability

The data set generated during the study are available from the corresponding author on request. If required, we will it make available in the University of Western Australian repository on request.

Requested additions

Supplementary information (Table S1 and Figures S1 - S8) and extended data (Table S2) are presented with this paper.

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Methods

Principles

Research relationships between Indigenous Australians and others involves complex issues of principle and ethics. The intense and continuous impacts of British colonisation and dispossession continue for Indigenous people today, contributing to extreme rates of mortality, morbidity and incarceration. Colonisation and post-colonial impacts affect almost every part of Indigenous people's lives today. Cross-cultural research in Australia demands engagement to 'do not harm' and counter these effects. We work within a positivist paradigm building on the strengths of people.

Authorship

Authors of this article includes individuals and a collective of Martu elders and traditional knowledge experts. Being the senior authors, they are listed last as is consistent with academic convention. The 'elders' entity is because of the unique and complex nature of Australian Indigenous knowledge traditions which accumulate from multiple oral, visual and experiential sources. The 'expert' entity recognises the contributing Martu individuals who are not elders but who chose to specialise in knowing and sharing their cultural knowledge.

The non-Indigenous authors are an interdisciplinary team who span natural and social sciences. Their disciplines encompass ethnoecology, arid zone ecology, botany, zoology, entomology, fine art, environmental engineering, hydrology and natural resource management. Collectively, the non-Indigenous authors hold over 130 years of field experience in Australian arid systems.

In the 1980s, knowledge shared by Martu elders was recorded by F.W. It is foundational to this article and provided its starting point. In 1987, Martu knowledge and practice was recorded at the initial request of Martu leaders (especially Ned Gibbs Milangka and Lucy Gibbs Purungu). Twenty-three Martu elders and experts spanning three generations provided specific information related to termites. Nineteen of those people have since passed away.

After Indigenous consultation then literature review and discussion, we challenge the prevailing Western scientific paradigm of authorship by individuals or groups of individuals. We considered co-authorship precedents in Australian and international literature. Previous work has found that less than 14% of Australian publications on Indigenous biocultural knowledge were co-authored[46]. Precedents in ecological publications include co-authorship with individual Indigenous authors[47], Indigenous communities[48], Indigenous corporations[49], and Indigenous countries[50,51]. None of these precedents are appropriate to our context so we use an authorship that reflects desert Indigenous multiple and cross-generational custodianship of knowledge. For future research, we are now developing partnerships with Indigenous organisations.

We appraised publications in the scientific literature about 'fairy circles' for information on First People's knowledge. In the publications, we searched for details in their background information, introductions, activities and processes in the methods, and people and organisations in the acknowledgements. Of the 27 papers considered, none included Indigenous authors, none included any activity to gain First People's knowledge, and only two papers (7%) thanked First People for help (administration and field work). Three papers (11%) include one or sentences on a local myth attributed to Himba and/or Damara peoples about fairy circles[52-54]; one of these papers cited a television show as the ultimate source of this information. This is despite San rock art interpreted to be flying termites and termitaria[55].

Ethics approvals

The 1988 – 1993 ethnographic work amongst Martu (F.W.) was funded by The University of Western Australia, Australian Institute of Aboriginal and Torres Strait Islander Studies (AIATSIS) and the Aboriginal controlled organisation, Western Desert Puntukurnuparna Aboriginal Corporation. Formal and informal ethics permissions were provided by these organisations. Information from Martu recorded by Walsh contributed to the successful Martu Native Title Determination.

Data in this paper predominantly derives from this past work and desk top research. We are guided by the core principles of the Martu organisation[56] and national ethical guidelines[44].

Ethnographic methods

We used multiple methods, sources and media to gather and analyse Indigenous People's knowledge related to harvester termites and their pavements. This information is fragmented and widely dispersed. Communication with archaeologists, anthropologists, linguists, historians, art specialists and others, including five recorded interviews, has yielded access to primary and secondary sources. We also searched Aboriginal language dictionaries, unpublished and published narratives, photo and film archives and other repositories. Tertiary sources in ethnographies, biographies and more have been scanned. Aboriginal artworks and associated documentation have been particularly informative. Triangulation and cross-checking helped corroborate and clarify details. Further searches would yield more ethnographic information. We mapped the exact or approximate locations of ethnographic records to show the span of termite-related knowledge across language regions (Figure 2a, Figure S2).

We spoke with six Martu people and two Warlpiri – Pintupi people about termites in 2021, with further interviews with Indigenous and other people planned for the future.

From interviews, dictionaries and linguists we accumulated a list of 114 words that span 15 Aboriginal dialects of arid Australia. This list will expand and is available on request. These terms relate to termites and their human ecology, including specifically to harvester termites and pavements. Challenges in identifying records associated with harvester termites or their pavements include the bias of Euro-Australians against termites[21], and misidentifications and mis-transcriptions by primary recorders of both termites and pavements[57].

Videos and photographs

Photographs and especially videos provide further evidence of Aboriginal uses of pavements. Three videos from the late 1980s show seed threshing directly or in pits excavated into pavements. One is narrated by a Pitjantjatjara woman. Links to these videos can be found at Figure S3. Audio-visual content is a compelling medium for Aboriginal audiences and future project partners, around which knowledge, trust and dialogue can grow.

Compilation and analysis

Original source materials from the ethnography, photos and videos were collated into a sortable spreadsheet. To determine the suite of uses and values attributed to harvester termites, these data were analysed thematically by uses, locations, people and artists associated with pavements, flying termites and more. The locations are shown in Figure 2.

Artworks

Desert Aboriginal artworks encode deep, rich, layered knowledge, some intertwined with ceremonies, sites and songlines[53]. Some meanings may be hidden from viewers. In the past, this art has rarely been explored for its ecological content. The Kaapa Tjampijinpa painting (Figure 1b) was the first desert artwork of termites and pavements we found. Art historian John Kean provided documentation for this work in 1976, recorded from Kaapa by historian Dick Kimber. Through such peer-to-peer contacts and a snowballing technique, we interviewed, searched, and found more and more artworks on the topic. One important step was art historian Vivien Johnson directing us to the works of Michael Nelson Jagamara[58] who painted flying termites and their pavements as eight of his primary Dreamings (Figure S5).

These paintings and their documentation were compiled into an Excel spreadsheet. There are more artworks to be found. We have not yet investigated flying termite-related icons in rock art[19,55].

We repeatedly cross-checked the artworks to our word list and ethnographic records. There are ethical and methodological challenges in interpreting Aboriginal art. For example, Kaapa Tjampijinpa, Michael Jagamara and other men's paintings were titled 'Watanuma', as were paintings by the women Wintjiya Napaltjari and Yuyuya Nampitjinpa. Were they all painting the same place? Why would women be painting a men's place and vice versa? As many small pieces of information accumulated, we concluded that there are two sites known as Watanuma or synonyms, located approximately 130 km apart and associated with different features of flying termites and with termite pavements. The abundance and mysteries of Aboriginal art related to termites may continue to reveal themselves.

Biophysical survey

Termite nests can be difficult to find, as 90% of species make subterranean nests, whereas mound-nests which are easier to see being above the ground. In Australia, most harvester termite species have subterranean nests. Some harvester termites construct 'pavement nests', so-called because the upper surface of the nest abuts the soil surface and is flat and hard resembling a concrete pavement. Pavement nests are not uniform; they often have varied sizes, shapes and features[10,59]. Some have small bumps or low mounds positioned anywhere on the pavement. Pavements may lie hidden under centimetres of windblown sand. One colony may build several pavement nests (i.e., they are polycalic), and move between them (i.e., not all pavement nests are occupied simultaneously). This movement between pavement nests is thought to be related to harvesting of grasses around each nest thus foraging holes (leading from the underground tunnels to the soil surface) are not maintained permanently. Termite nests may be colonised by other termite species, ants or other insects, fungi, with or without the original inhabitants. Pavements may persist for decades or more after the termites die or relocate, although termite structures can degrade in a few years after fire or flood. We have observed unoccupied pavements which have been burnt and damaged by hot wildfires and then erosive rain.

In July 14-21, 2021, in the East Pilbara of Western Australia, we surveyed plots on Nyiyaparli country east of Newman airport and near the Jigalong Road turnoff (Figure 2c). Four plot areas were selected at the same locations surveyed by Getzin et al.[2,9]. Following the first, subsequent subject pavements were selected by nearest neighbour proximity. We recorded latitude and longitude and the north-south and east-west diameter of each pavement. In total, we excavated into 25 pavements in the surrounding spinifex grassland, similar excavations adjacent to 11 of these pavements. The first pavement was used to develop our methods, with results presented from the next 24 pavements (Figure 4). In 16 pavements, three trenches were dug and in the remainder one trench was dug at 50 cm long, 15 cm wide, 15 cm deep. The first trench was dug in the centre of the pavement, and the others toward the edge and on opposite sides of the pavement (Figure S7). In total, 29 m of trench were dug on the pavements, plus four metres in the trial pavement.

We improved on previous methods[2,14,3,9] by sampling longer trenches, using better excavation tools including an air blower. Longer trenches revealed more of the pavement substructure, and we used tools that were less likely to shatter the termite structures. These tools were a mattock or crowbar, or an 18V electric power tool with an 8 cm shank blade by contrast to a jack hammer used by Getzin et al.[3,9]. After excavation, we used an 18V air blower to remove excavation debris and dust which made the termite structures easy to see.

In the initial test pavement, we dug deeper, longer, and more holes (Figure S7), trialling different tools including a hand chisel and a teaspoon. We did not include quantitative results from this pavement in the analysis. From this first pavement we concluded that with the tools and time available it was not possible to dig to the bottom of the consolidated soils on the Newman pavements. Heavier machinery and alternative methods are needed to examine the deep structure of the pavements.

Adjacent to the test pavement in the spinifex grassland, we trialled trenches and pits. Adjacent to 11 pavements we cleared vegetation then excavated three trenches dug at 50 cm long, 15 cm wide, 15 cm deep (as for pavements). We cleaned these with the air blower.

Observations included presence/absence of termite chambers, termite frass chambers, termite chaff and/or termite workers or soldiers. Other observations were recorded as required, and each pavement and trench were photographed. Samples of termites, termite chaff, termite chambers and consolidated soils were collected. A single observer reported their observations to the data recorder for the first 16 pavements. One person did all tasks on the other eight pavements.

All data was written into printed data sheets. Quantitative records were presence/absence of termite chambers, termite frass chambers, termite chaff and/or termite workers or soldiers. Qualitative observations were also recorded for each trench. Each pavement and each trench in each pavement were photographed. Samples of termites and termite chaff were collected and labelled. Samples of termite chambers and consolidated soils were taken from the methodological pavement.

At the end of surveying each plot, all trenches were backfilled. The surfaces were flattened and raked flat, and spinifex returned over the sandplain trenches.

All photographs were labelled with the plot and pavement numbers. Quantitative and qualitative data from the printed data sheets were transcribed to an Excel spreadsheet.

Species identifications

Distribution maps[60] indicated both *Drepanotermes perniger* and *D. rubriceps* occur near our sites in the east Pilbara and also on Ngalia Warlpiri country, at Australian Wildlife Conservancy's Newhaven Wildlife Sanctuary (Newhaven). Termites from excavations were collected (Figure S7b). All termites from the Newman pavements were keyed and identified as *D. perniger.* One other species, probably *Shedorhinotermes derosus*, was found in shallow chambers under spinifex adjacent to pavement FC2-7 near Newman. Termites from Newhaven pavements were also keyed as *D. perniger*, again, two *Drepanotermes* species were possible.

Newhaven pavement reconnaissance excavation

During 1 – 2 May 2021, at Newhaven, we explored features of one pavement. This pavement (1.4 m by 1.2 m diameter) was sprayed with 50 L of water to observe water behaviour on the pavement. One side of the pavement was vertically cut through to examine its internal structure and to collect termites. The surrounding sandy soils were soft enough to dig by hand. Two north – south trenches were dug beneath the pavement then connected by a tunnel under the full pavement. A scale drawing of the excavation was prepared on site (Figure S8c, d). While *D. perniger* occupied both the Newhaven and the Newman pavements, pavements from these two localities showed very different structures (the Newhaven sample size is small).

Track-based observations

Termite pavements are obvious within many unformed vehicle tracks which traverse suitable landforms. Pavements are resistant to road graders, vehicle traffic and water erosion, will stand up to a few centimetres above the track surface. We have incidental observations of pavement occurrences from tracks (Figure 2a). Track-based surveys could be used to determine densities of termite pavements.

Aerial methods

Figure 2 records our aerial observations of termite pavement spot patterns using drones, helicopter and Google Earth images across the arid regions of Northern Territory, Western Australia, and South Australia. These states and territory are where we have on-ground experience and familiarity with landforms and ecosystems. *Drepanotermes perniger* and *D. rubriceps* each have much wider continental distributions including in Queensland and New South Wales[60].

Drones and helicopters were used on four occasions for incidental pavement observations. We also gathered ground and aerial records provided by colleagues familiar with pavements. Systematic methods for aerial survey are required.

Google Earth was used to identify locations with clearly visible pavement spot patterns in spinifex vegetation. Pavement spots, if present and not obscured by sand, are visible at approximate one kilometre altitude. We can distinguish pavement spots from spinifex rings or other circular formations and did not confuse them[10]. Factors that obviate the clarity and confidence of identification of spots include lower resolution satellite images and the sparseness or absence of spinifex vegetation cover (typically reduced by wildfires). To detect pavement spot patterns, we looked within the prospective land units (spinifex grasslands) for darker areas where denser vegetation made spot patterns more visible (Figure 2). The ‘historical imagery’ function on Google Earth can allow observation prior to fire events which can obscure pavement spot patterns.

Figures

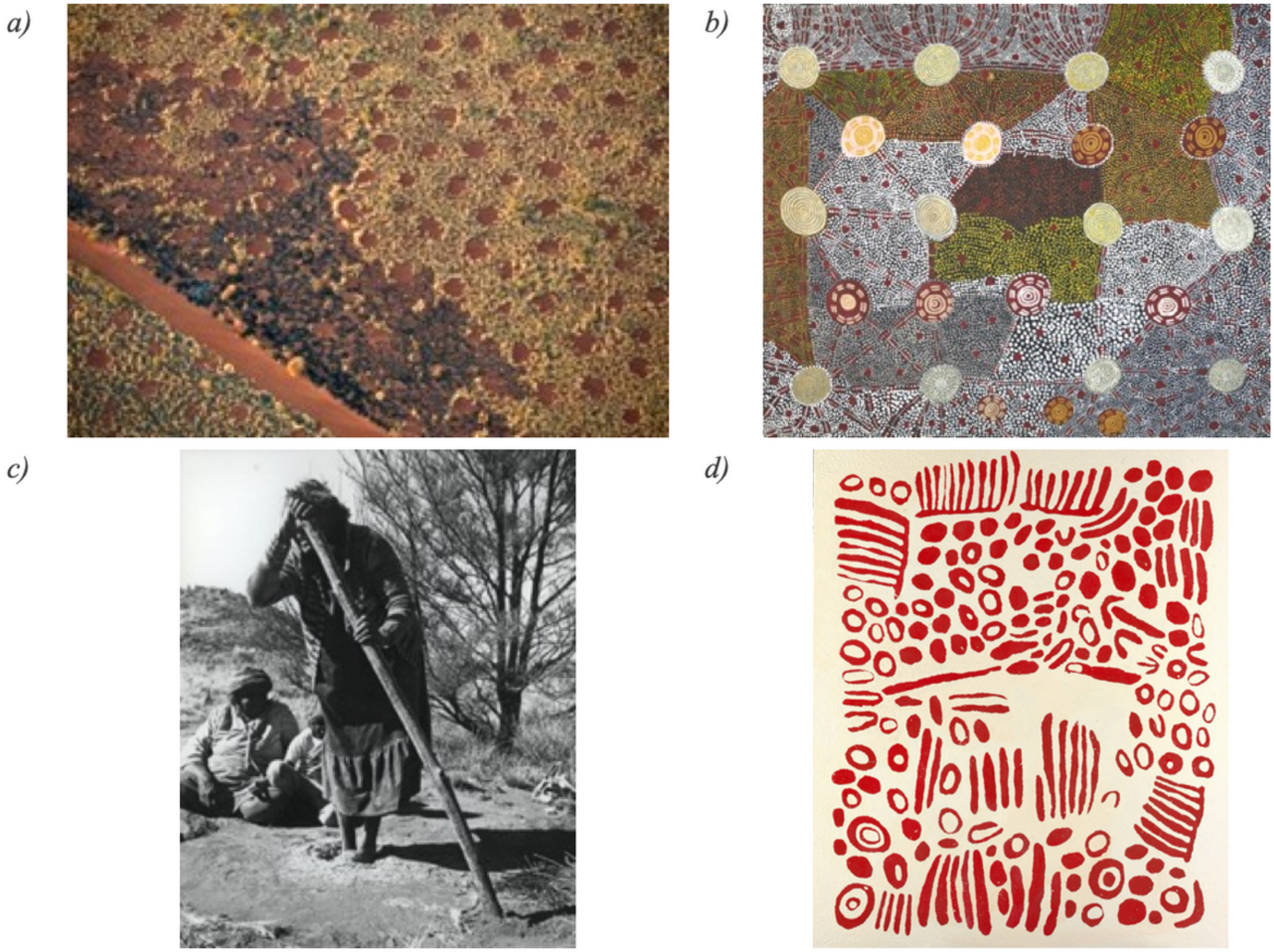

Figure 1

a) Termite pavement spots in spinifex grassland of *Triodia basedowii* on Nyiyaparli lands near plot FC-2. Dark ash of recently burnt spinifex is seen along the track. (Photo by Mike Gillam). b) Painting by Anmatyerr man, Kaapa Tjampijinpa, titled ‘Watanuma’ (1976), Synthetic polymer paint on canvas, 202.4 x 171.8 cm. National Museum of Australia[16]. c) Pitjantjatjara woman, Nganyinytja Lewis, uses feet and pole to thresh seed in a pit she excavated into termite pavement.[17]. d) Painting by Pintupi woman, Wintjiya Napaltjarri, ‘Watanuma’. (2008), Synthetic polymer paint on canvas, 151.2 x 182.0 cm. National Gallery of Victoria, Melbourne. Watanuma translates to edible winged termites, a Dreaming place and other meanings. Both ‘Watanuma’ places are surrounded by harvester termite pavements of *Drepanotermes perniger* and possibly *D. rubriceps*. Figure S1 interprets each image. Both paintings are © the artist licensed by Papunya Tula Artists and Aboriginal Artists Agency.

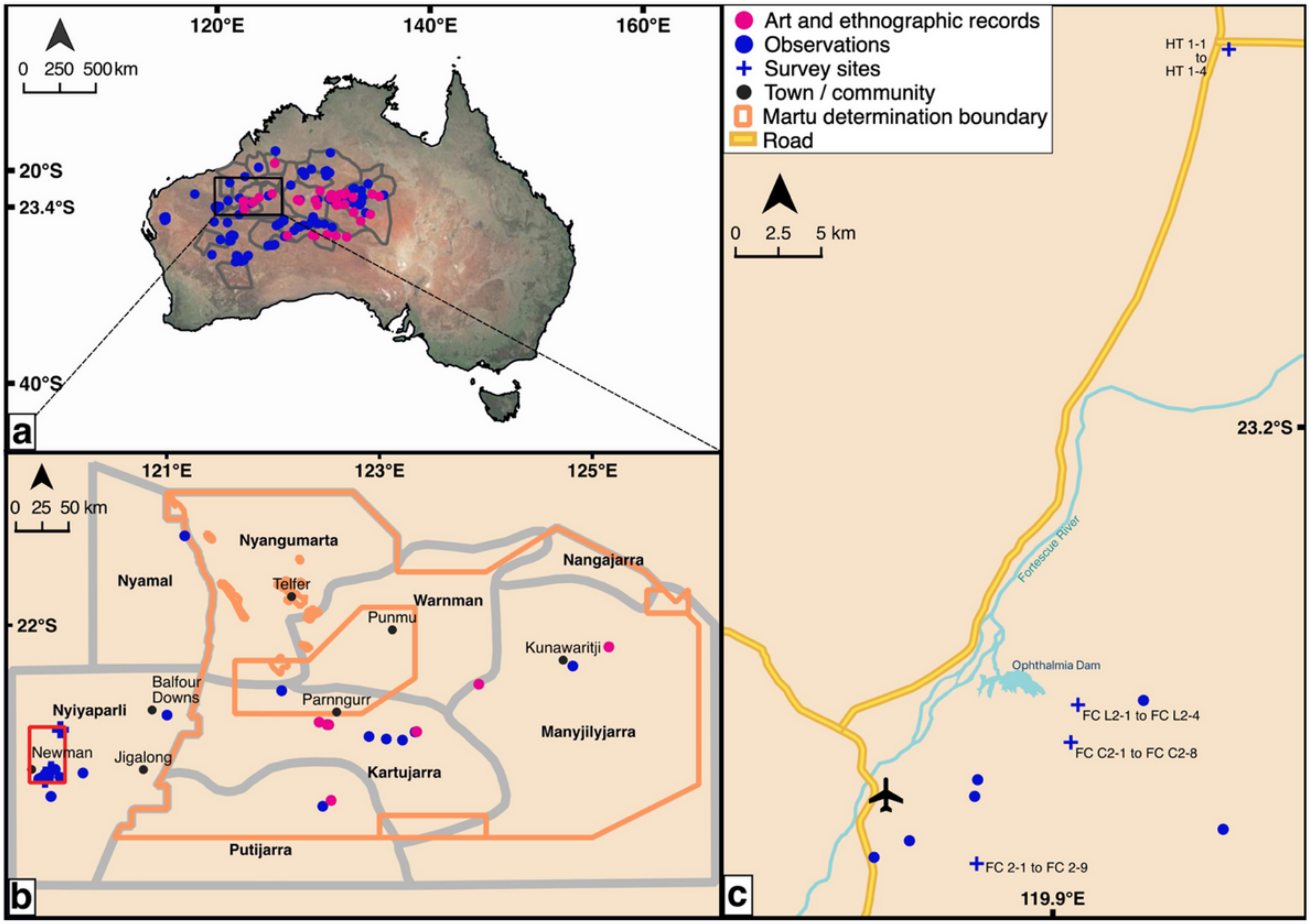

Figure 2

a) Locations of Indigenous art and ethnographic records of termite pavements and winged termites, and observations of termite pavements across Aboriginal language groups in Western Australia, the Northern Territory and South Australia. Other states have not been searched or mapped). Observations include via survey sites, photos and videos, and satellite imagery (see methods). Ethnographic records and pavement observations in New South Wales and Queensland have not been searched for or mapped. Language boundaries are in grey, language names in Figure S2. Note that all language boundaries are permeable, dynamic and often contested due to displacement, dispossession, relocation and other factors. b) Martu language areas and the Martu Native Title Determination Boundary with ethnographic records and pavement locations, with neighbouring Nyiyaparli lands to the west (boundary approximate; shape files adapted from Kanyirninpa Jukurrpa). c) East of Newman airport, 2021 survey plot locations plus observed termite pavement areas.

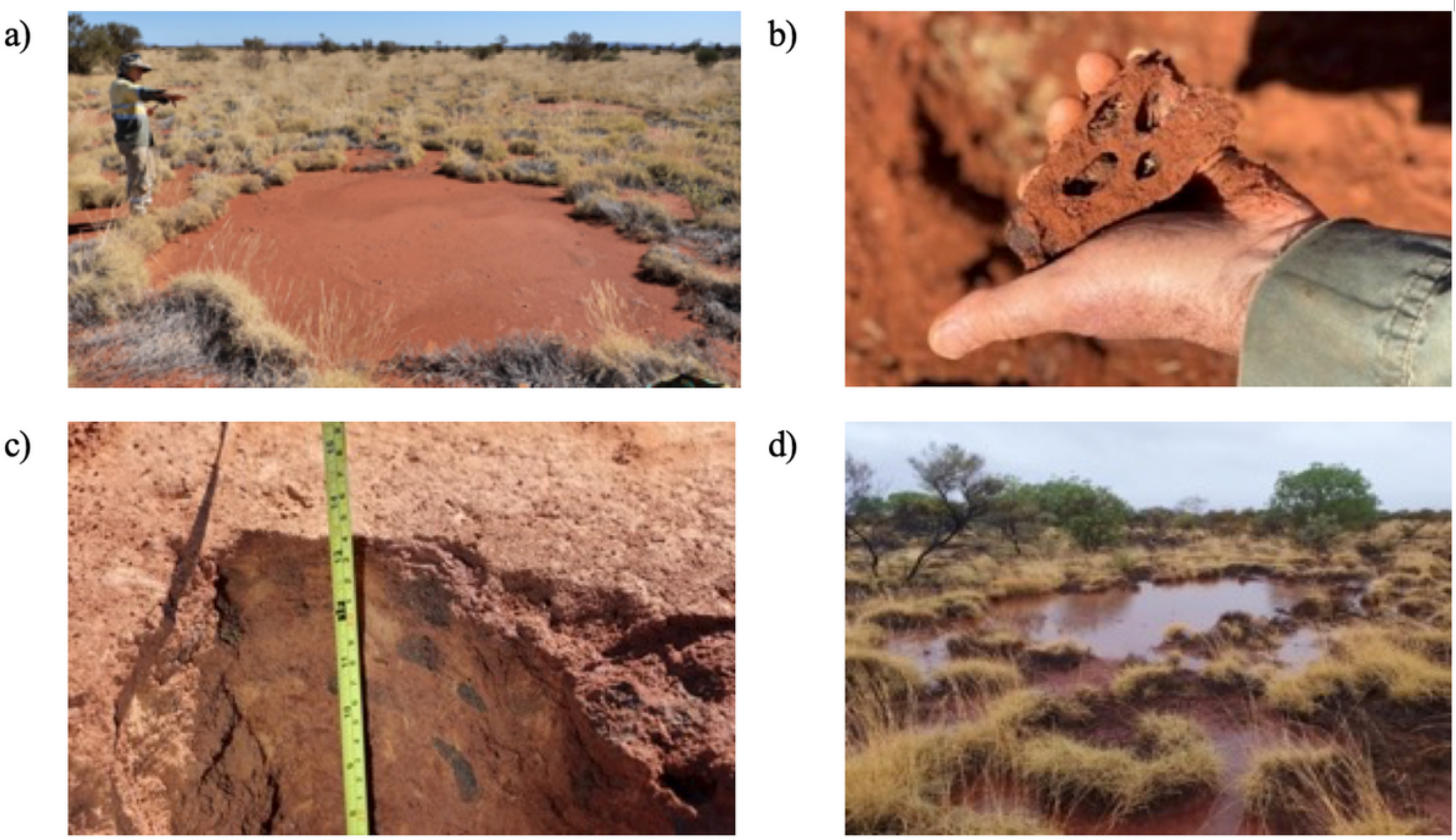

Figure 3

Aboriginal peoples' knowledge was compared to a survey of pavements on Nyiyaparli country. a) Typical pavement surveyed in same plot area as Getzin et al.[2,9] and within 200 m of Figure 1a. This pavement averaged 5.2 metres diameter with no mound, in dense spinifex grassland unburnt since at least 1985. b) Termite structure extracted from the pavement showing termite chambers, spinifex chaff stored in chambers, chambers with blackened walls, and all within dense consolidated soil. c) Dark termite frass-filled chambers and the dense termite cement distinguished the on-pavement structures to the inter-pavement soils that were loose and easy to dig. Frass chambers were 1-3 cm long. d) Observations showed that termite pavements held rainwater for short time periods, but for longer than the inter-pavement sandplain areas. Such observations are rare today as these areas are often inaccessible by vehicle during rain (Photo by Emma Stock, < 6 km west of site FC 2-1).

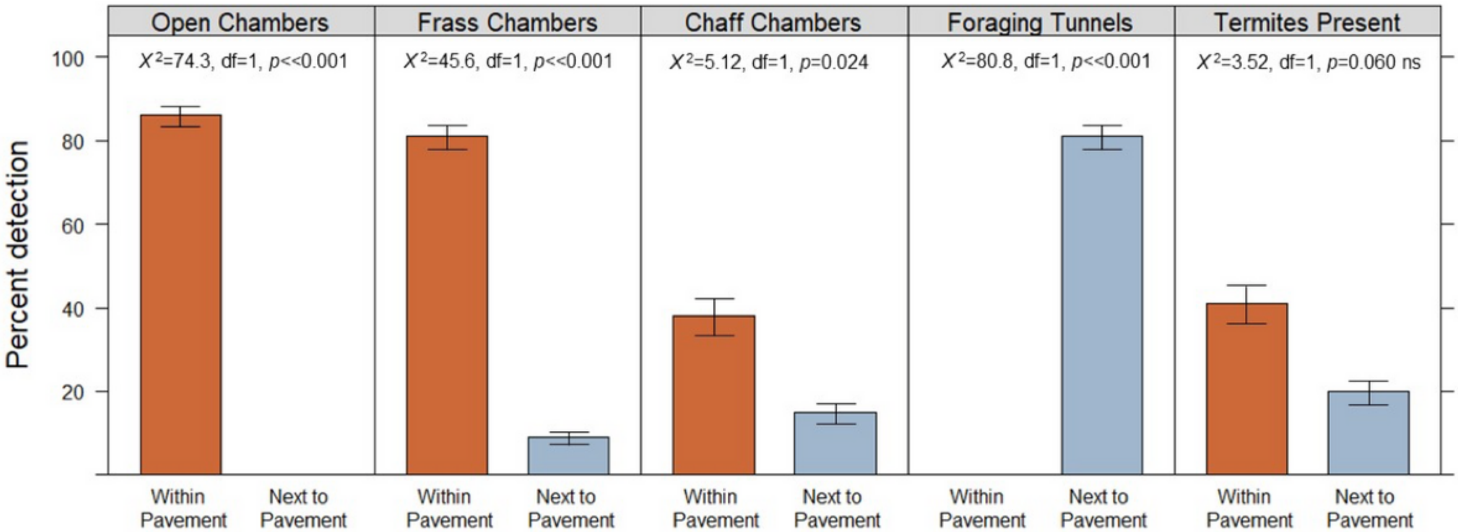

Figure 4

Within pavements, termites and termite structures are more common than in the spinifex grassland next to pavements. At the Newman plots, all chambers and almost all permanent galleries were found within pavements, whereas temporary foraging tunnels were found in the grassy inter-pavement areas. Termites and grass chaff were found in both, but at significantly different frequencies. Samples sizes: 24 pavements and 24 areas next to pavements (the former included 29 m of trenching in total). Error bars indicate standard errors.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryandExtendedData.docx