



**Late Pleistocene/Early Holocene sites in the montane forests of New Guinea yield early record of cassowary hunting and egg harvesting**

Kristina Douglass<sup>1,2,3\*</sup>, Dylan Gaffney<sup>4</sup>, Teresa J. Feo<sup>3,5</sup>, Priyangi Bulathsinhala<sup>6</sup>, Andrew L. Mack<sup>7</sup>, Megan Spitzer<sup>3</sup>, and Glenn R. Summerhayes<sup>8, 9, 10</sup>

<sup>1</sup>Department of Anthropology and Institutes for Energy and the Environment, The Pennsylvania State University, University Park, PA 16802

<sup>2</sup>Department of Anthropology, National Museum of Natural History, Smithsonian Institution, Washington, DC

<sup>3</sup>Department of Vertebrate Zoology, Division of Birds, National Museum of Natural History, Smithsonian Institution, Washington, DC

<sup>4</sup>Department of Archaeology, University of Cambridge, Cambridge, CB2 3DZ, United Kingdom

<sup>5</sup>California Council on Science and Technology, Sacramento, CA

<sup>6</sup>Department of Statistics, The Pennsylvania State University, University Park, PA

<sup>7</sup>Academic Affairs, The Pennsylvania State University, Altoona, PA 16601

<sup>8</sup>Archaeology Programme, School of Social Science, University of Otago, P.O. Box 56, Dunedin 9054

<sup>9</sup>School of Social Science, University of Queensland, Brisbane, Queensland 4072, Australia.

<sup>10</sup>College of Asia & the Pacific, Australian National University, ACT, Australia

\*Corresponding author: Kristina Douglass; [kdouglass@psu.edu](mailto:kdouglass@psu.edu)

The authors declare no competing interests.

ORCIDS:

Kristina Douglass: 0000-0003-0931-3428

Dylan Gaffney: 0000-0003-4869-9730

Teresa J. Feo: 0000-0002-4189-8692

Andrew L. Mack: 0000-0001-8823-9101

Megan Spitzer: 0000-0002-8878-2443  
Glenn R Summerhayes: 0000-0002-0654-1305

### **Classification**

SOCIAL SCIENCES – Anthropology  
BIOLOGICAL SCIENCES - Ecology

### **Keywords**

Montane rainforests; Pleistocene/Holocene transition; Sahul; megafauna; ratites; cassowary; human-avian interaction; hunting; eggshell; microscopy

### **Author Contributions**

KD, DG, TF, PB designed research; KD, TF, PB and MS performed analyses; DG conducted sample identification; GRS provided collection access; AM contributed field data and photos; KD, DG, TF, PB and AM wrote the paper; all authors edited the paper.

### **This file includes**

Main Manuscript  
Figures and Tables  
Supplement

### **Abstract**

How early human foragers impacted insular forests is a topic of broad scientific interest. Paradoxically, terminal Pleistocene and Early Holocene impacts of foraging communities have been characterized as both extreme—as in debates over human-driven faunal extinctions—and minimal compared to later landscape transformations by farmers and herders. We investigated how rainforest hunter-gatherers managed resources in montane New Guinea and present some of the earliest documentation of Late Pleistocene through Mid-Holocene exploitation of cassowaries (Aves: Casuariidae). Worldwide most insular large birds were extirpated by the Late Holocene, following human arrivals, including elephant birds of Madagascar (Aepyornithidae) and moa of Aotearoa/New Zealand (Dinornithiformes)—icons of anthropogenic island devastation. Cassowaries are exceptional, however, with populations persisting in New Guinea and Australia. Little is known of past human exploitation and what factors contributed to their survival. We present a novel method for inferring past human interaction with mega-avifauna via analysis of microstructural features of archaeological eggshell. We then contextualize cassowary hunting and egg harvesting by montane foragers and discuss the implications of human exploitation. Our data suggest cassowary egg harvesting may have been more common than the

harvesting of adults. Furthermore, our analysis of cassowary eggshell microstructural variation reveals a distinct pattern of harvesting eggs in late ontogenetic stages. Harvesting eggs in later stages of embryonic growth may reflect human dietary preferences and foraging seasonality, but the observed pattern also supports the possibility that—as early as the Late Pleistocene—people were collecting eggs in order to hatch and rear cassowary chicks.

## Significance statement

Eggshell is an understudied archaeological material with potential to clarify past interactions between humans and birds. We apply a novel analytical method to legacy collections of Late Pleistocene to mid-Holocene cassowary eggshell and demonstrate that early foragers in the montane rainforests of New Guinea preferentially collected eggs in late stages of embryonic growth. This finding suggests that foragers regulated the exploitation of cassowaries and may have hatched eggs to rear chicks. The montane rainforests of New Guinea may thus present the earliest known evidence of human management of avian breeding, preceding the domestication of chicken (*Gallus gallus*) and geese (*Anser anser*) by millennia.

## Main Text

### 1. Introduction

Once considered marginal environments ill-suited to human colonization, tropical rainforests have yielded substantial evidence of diverse adaptive strategies from the Late Pleistocene (LP) through the Holocene (1). Montane rainforests present additional challenges to human occupation in terms of resource acquisition, locomotion, and thermoregulation. Recent research has further demonstrated the adaptive flexibility of *Homo sapiens* and reinforced the need to rethink the range of dynamic interactions between humans and rainforest environments (2). In this paper we present the first intensive study of pre-modern cassowary (*Casuaris* spp.) hunting and egg collecting in Sahul/Asia-Pacific during the LP and Holocene. Native to the rainforests of northeastern Australia and New Guinea, and by far the largest extant native vertebrate on New Guinea, this keystone taxon presents a unique opportunity to gain insights into the complex interactions between human communities and rainforests (Figure 1). We ask whether archaeological remains of cassowary—bone and especially eggshell—reflect intentional human management of cassowaries by mobile foragers and discuss the far-ranging implications of human–cassowary interactions in terms of the composition and persistence of rainforest communities. Specifically, we present a novel multi-analytical approach for evaluating eggshell microstructures associated with embryonic development. Using 3D laser microscopy to scan eggshell surfaces, we combine statistical modeling of surface texture with visual assessments of microstructural morphology, in order to assign archaeological eggshells to stages of ontogeny

(Figure 2). In particular, the appearance of pitting at the tips of the eggshell mammillary cones is an indication of more developed stages of embryonic growth (see S1.10). We then use these ontogenetic assignments to characterize patterns of human exploitation (3). We focus on archaeological assemblages spanning the Last Glacial Maximum (LGM) through the Late Holocene (LH) from two rock shelters—Yuku and Kiowa—in the montane rainforests of eastern New Guinea (Figure 3), and report a series of new  $^{14}\text{C}$  dates to further resolve the chronology of eggshell collecting at these sites (Fig. S 10). The analytical method we present has great potential to elucidate human interactions with avian species globally, and may greatly expand our understanding of the decline and extinction of many large flightless birds following human colonization of new regions.

The extent to which foraging societies transform landscapes through resource use and management is an enduring question in anthropology and historical ecology (4, 5). Despite widespread evidence of ecological shifts correlated with land-use by foraging communities and compelling examples of forager niche construction (6-8), the view that agriculture results in more intentional and intensive landscape-level changes persists—particularly in periods preceding Late Holocene global land-use (9). However, these assumptions about the minor influence of foraging communities on landscapes are inconsistent with behavioral ecology models of predator–prey dynamics that have been applied to investigations of the impacts of hunter-forager societies on populations of prey species (10). These models predict that broad-spectrum predator species likely have more significant impacts on the population dynamics of individual prey species, as predators with flexible resource use are less sensitive to changes in the population dynamics of individual prey than specialized predators. These models, when applied to study the differential impacts of *Homo sapiens* versus other hominins on Late Pleistocene environments, support the possibility that Late Pleistocene extinctions of vertebrate fauna were driven by in-migration by more flexible populations of *Homo sapiens* (11). More importantly, assumptions that foraging communities influence landscapes in minimal ways, are inconsistent with the intergenerational knowledge of many Indigenous peoples, which indicates that traditional land-owners and their ancestors have intentionally and intensively cultivated expansive landscapes, in some cases for millennia (12, 13).

Montane New Guinea presents an important case study for clarifying forager impacts on forest landscapes over extended time-scales. Humans had reached northern Sahul by at least 42,000 years ago and the initial peopling of the region included rapid exploration of montane environments (14). The archaeological record demonstrates that early activities in the mountains involved the collecting of *Pandanus* nuts, transporting yams from the coast, forest burning, marsupial hunting, and the production of large ‘waisted’ stone axes (15, 16). The highlands during this time were dominated by lower montane rainforests of beech trees (*Nothofagus*, *Lithocarpus*, and *Castanopsis*), with subalpine forests of pines (*Phyllocladus*) and conifers (*Dacrycarpus*, *Podocarpus*, and *Papuacedrus*) above that, and more open grasslands and shrubs



at higher altitudes (17). Modern human genomic studies indicate Pleistocene populations frequenting the highland zone were in the order of a few hundred or thousand people (18). These populations were relatively stable until the end of the LGM when populations rapidly increased, with montane societies becoming relatively isolated from the lowlands by the start of the Holocene (19). These population increases co-occurred with climatic amelioration at the terminal Pleistocene and Early Holocene, which saw average temperatures increase by about 7°C in the montane zone and rainforests expand further upslope, with the treeline shifting from 2200 m asl to almost 4000 m asl (20). Moreover, this period saw some groups increasingly focus their subsistence on wetland cultivation of tubers and tree crops in some inter-montane valley systems (21). Despite these changes, montane rainforest foraging persisted as the primary mode of subsistence in other valley systems into the mid-Holocene (22), leading to regional variation in anthropogenic landscape modification and forest clearance (2, 23).

Although there is evidence that humans shared the montane zone with megafauna including giant kangaroos (*Protemnodon* spp.), Diprotodontids, the marsupial wolf (*Thylacinus cynocephalus*), and cassowaries (*Casuarius bennetti*) for several millennia (24, 25), it is unclear the extent to which these species were a focus of early hunting. There is no clear evidence that Pleistocene humans drove megafauna species to total extinction, but cassowaries are the only native large-bodied vertebrate species extant in the mountains today (26). Though the faunal record is patchy, some archaeological sites do provide evidence for local extirpation, including species of fruit bats (*Aproteles bulmerae*), marsupial wolves (*Thylacinus* sp.), and rodents from the Mt Elimbari area by the mid-Holocene, cuscus (*Phalanger* spp.) from the Mt Hagen area by the Early Holocene (2), and wallabies (*Thylogale christensenii* and *Thylogale brunii*) from the Nemangkawi mountains in western New Guinea sometime after the mid-Holocene (27, 28). These extirpations could have been driven by forest clearances, deliberate fires used for hunting, direct capture, trapping, and competition from introduced species, including pigs (*Sus scrofa*) and dogs (*Canis* sp.) (29).

Little is known about the nature of early exploitation, but cassowary hunting and rearing of chicks has been documented ethnographically, and on New Guinea the birds and their feathers are highly valued in trade and ritual today (30, 31, 32; Figure 1). Regional evidence confirming early human–cassowary interaction (Table S 3), includes eggshell directly dated to around 20 ka BP from Toé cave (33, 34), around 16 ka BP (by association) on the Aru Islands formerly connected with Sahul (35, 36), and possibly dating to 25 ka BP (by association) at Nombe (25) (Figure 3). Cassowaries are unmistakable, large flightless ratites that inhabit the understory of wet, dense forests in northeastern Australia and New Guinea (37; Figure 1). They are primarily frugivorous and are an important disperser of large-seeded plants (38–40). The three extant species of cassowary in Australia and on New Guinea are currently in decline due to human pressures, including habitat destruction, hunting, and predation on eggs and young by introduced predators (37, 41, 42). Nevertheless, cassowaries on New Guinea are notable in their persistence

following human arrival, as most large flightless birds on islands—including Madagascar’s elephant birds (Aepyornithidae) and Aotearoa/New Zealand’s moa (Dinornithiformes)—were extinct by the Late Holocene (43, 44).

We investigate Late Pleistocene and Holocene patterns of human exploitation of cassowaries at two rockshelter sites—Yuku and Kiowa (Figure 3; S1.1). These sites preserve deep zooarchaeological sequences that allow us to examine the temporal dynamics of hunting and faunal extirpation (45). Yuku in the Lanim Gorge on the northwest slope of Mt Hagen was occupied by at least the end of the LGM, 17,500 years ago until the recent past, while Kiowa near the Mae river valley on Mt Elimbari was occupied at the terminal Pleistocene, 12,000 years ago until the last few centuries. Both sequences suggest early foragers supplemented a plant-rich diet with broad spectrum hunting, leading to the capture of almost all available mammalian game. At Kiowa, fruit bats and cuscus were also captured in large quantities suggesting human hunters specialized in capturing a small number of reliable species (2). Polished axes traded in from nearby valley systems provide evidence for trade links connecting these sites with other areas in the mid-Holocene (23) and marine shell and pottery indicate exchange connections to the hilly lowlands and coast had formed by the last millennium BP (46, 47).

## **2. Results**

The results reported below are supplemented by additional tables, figures and extended descriptions in the supplementary information. All supplementary information is referenced parenthetically in the text below.

### ***2.1 Chronology***

We obtained 15 new  $^{14}\text{C}$  measurements on cassowary eggshell from Kiowa and Yuku and combined these with previous AMS determinations ( $n=10$ ) derived from avian eggshell at these sites (Table S 1; Fig. S 10). These new dates confirm that the human occupation and evidence for the exploitation of cassowaries at Yuku extends from the end of the LGM (ca. 17.8k cal BP) through the Early Holocene (ca. 9.5k cal BP), while Kiowa’s occupation spans the terminal Pleistocene through Late Holocene (48). Evidence for cassowary exploitation at Kiowa, however, derives from contexts that span the terminal Pleistocene to Mid-Holocene (ca. 12.5k cal BP-6.5k cal BP; Fig. S 10). No evidence of egg harvesting was recovered for the Late Holocene.

### ***2.2 Cassowary bone***

All identifiable avian remains (Number of Identified Specimens [NISP]=28) were recovered from Kiowa and are referable to the genus *Casuaris*. Of these, 15 could be identified to the

species *C. bennetti* (Dwarf Cassowary). The smallest cassowary species and a montane forest resident, it would have been the locally available cassowary for Kiowa. The overwhelming majority (71%, NISP=20) of cassowary bones were recovered from Unit EE and span the terminal Pleistocene through Mid-Holocene (ca. 12.5k cal BP to 6.5k cal BP; Table S 1; Fig. S 10). Within EE, Level 4 had the most cassowary elements (29% of EE, NISP 8; 7,169–6,984 cal BP [90.2%]). Unit SE contained 35% (NISP 7) of the cassowary bones, all but one of which were collected in Mid-Holocene levels. Finally, Unit EB only produced one identifiable element (femur shaft fragment), recovered from a Mid-Holocene deposit. All of the elements, with the exception of 3 fragments of a pelvis most likely from one individual, are from the hind limb. The vast majority (57%) are from the tibiotarsus. The femur and tarsometatarsus each make up 14% of the total NISP. In addition, there is one fibula and an ungual phalanx (claw). All elements are fully ossified (i.e. osteologically adult).

### **2.3 Cassowary eggshell**

A total of 1019 fragments of eggshell assigned to *Casuaris* spp. were recovered from Kiowa (n=31) and Yuku (n=988). The vast majority of samples (n=884)—about 87% of the overall assemblage—were recovered from layers dated to the Terminal Pleistocene and Early Holocene (Fig. S 11; Table S 2). Approximate eggshell fragment surface area—used here as a proxy for degree of fragmentation of the assemblage—and estimated Minimum Number of Individuals (MNI) are given in Table 1. We observed little variation in the degree of eggshell fragmentation relative to chronological phase. Weathering, however, was not uniform across the two site assemblages (Fig. S 12), though no significant correlation was observed with regard to degree of weathering and chronological phase (Table S 4). Of the large proportion of samples dated to the terminal Pleistocene and Early Holocene, about 65% (n=571) displayed “light” or “medium-light” weathering (Fig. S 12).

#### **2.3.1 Prediction of eggshell developmental stage using a modeling approach**

NISP of eggshell according to predicted ontogenetic stage using the two statistical models (1-predictor and 4-predictor) are reported in Table S 5. Samples that were assessed as too weathered to distinguish morphological features were excluded (see Appendix S1.10). The majority of samples (~78%; n=800) are predicted to be “Late” stage eggs according to the 1-predictor model. When using the 4-predictor model, however, this trend changes and a large proportion of the eggshells are predicted to be “Middle” stage (~72%; n=740; Figure 4). There is greater agreement between the models with regard to eggshells predicted to be in the “Early” stage.

Agreement between the two models is  $= (13+165+231)/969=42\%$  (Table S 6). For example, a total of 545 samples that are predicted to have been harvested in the “Middle” stage using the 4-predictor model are predicted as “Late” stage using the one-predictor model. This could be due

to the fact that the 4-predictor model is picking up additional variation between the samples because it incorporates more surface roughness parameters (Sa, Ssk, Sku and Sz) than the 1-predictor model (Sa only; see Appendix S1.6, S1.7 and S1.9).

Our two predictive models of eggshell developmental stage each resulted in three marginal probability values, which represent the likelihood that each sample was harvested in the “Early”, “Middle” or “Late” stage of development (Dataset 1). The three probability values for each sample run through one of our models add up to 100%, and the highest probability value of the three is the identified stage of development. For example, an eggshell sample with marginal probability values of 60% for “Early”, 30% for “Middle” and 10% for “Late” is identified by the model as having been sampled in the “Early” stage of embryonic development. For eggshells predicted to have been harvested during the “Late” stage by the 1-predictor model, the marginal probabilities for “Late” stage are significantly higher on average than the probabilities for “Middle” and “Early” stage, providing a degree of confidence in the predictions (Fig. S 13).

The dominance of the highest marginal probability value is less pronounced for the predictions using the 4-predictor model, suggesting that the model is somewhat less “confident” in its predictions than the 1-predictor model (Fig. S 14). In other words, because the 4-predictor model may be picking up additional variation in surface roughness compared to the 1-predictor model, the difference between the predicted probabilities for the “Late” and “Middle” stages is less pronounced than in the 1-predictor model.

### ***2.3.2 Identification of eggshell developmental stage using visual assessment***

Visual assessment of microstructural features for each cassowary eggshell sample in the overall assemblage (n=1019) was conducted using a set of 4 high-resolution images (Figure 5) and 4 cross-sectional profiles (Fig. S 15; n=8152 total visualizations). NISP of eggshell identified as having been harvested in the “pre-pitting” (equivalent to the “Early” stage in the predictive models) versus “pitting” stage (equivalent to the later part of the “Middle” stage and to the “Late” stage in the predictive models) are reported in Table S 7. The vast majority of eggshells displayed pitting (CME categories 2 and 3; Figure 4). For example, in the terminal Pleistocene/Early Holocene assemblage, pitting was evident in ~62% of the samples (n=548), while ~19% (n=166) showed intact mammillary cones with no signs of resorption, and ~15% were too weathered to distinguish visually whether pitting had commenced. Samples assigned to CME category 3 clearly displayed pits, though some of the morphology showed signs of weathering that could affect the roughness measurements used in the predictive models.

### ***2.3.3 Comparisons of modeling approach and visual inspection***

Agreement between the two models and the visual inspection can be assessed by considering counts of “Middle” and “Late” stage predictions versus counts for CME categories 2 and 3 (green values in Table S 8 and Table S 9; Figure 4). These counts suggest broadly similar levels of agreement between these approaches. Of the samples where pitting was visible, 99% (596/603) were recognized as “Middle” or “Late” stage by the one-predictor model versus 98% identified as “Middle” or “Late” (591/603) by the 4-predictor model.

### ***2.3 Eggshell Color and burning***

Eggshell fragments in both assemblages varied in color (Fig. S 16). Color variation reflects both depositional context and sometimes degree of burning. Burning of eggshell exteriors was observed on 58% of the total assemblage, while interior burning was observed on 48% of samples. Excluding unstratified samples, exterior and interior burning were most prevalent on eggshells dated to the terminal Pleistocene and Early Holocene (Table S 10). Burning was also more frequently observed at Yuku than at Kiowa.

Paired observations of exterior and interior burning on samples predicted to have been harvested at different stages of development reveal some diachronic patterns, including burning on the exterior and interior of the majority of “Early” stage eggshells during the LGM and Late Pleistocene/Early Holocene (Fig. S 17 and Figure 6). During the LP/EH there is an increase in the occurrence of samples with no indications of burning, especially for those predicted to have been harvested in the “Middle” and “Late” stages of development.

We tested whether incidence of exterior and interior burning was correlated with eggshell developmental stage (Table S 11 and Table S 12). Both tests of independence revealed a significant association between incidence of burning and developmental stage.

## **3. Discussion**

Human use of avian eggs has been documented in some of the earliest deposits attributed to *Homo sapiens* and avian eggshell is thus a key material for understanding the evolution of complex human behaviors (49). The method we have developed to analyze eggshell microstructural variation has great potential to clarify past human interactions with avian species, and can be applied to new as well as legacy collections of eggshell from diverse time periods and contexts. Analysis of eggshell surface microstructures can offer insights into resource management decisions, as it can reveal patterns in the timing of egg harvesting, which itself can shed light on foraging strategies and seasonality, as well as dietary preference (e.g. consuming primarily yolk and albumen versus balut), and even the management of avian breeding (3, 50). Additionally, the method we present can be used to investigate the use of eggs—such as ostrich eggs in Pleistocene contexts (49)—as secondary products (e.g. liquid containers), which

presumably would have required selection of “Early” stage eggs with liquid contents that could be extracted without excessively damaging the shell.

The overarching question posed in this paper is whether cassowary bone and eggshell assemblages recovered from Kiowa and Yuku reflect strategic harvesting and management of cassowaries by mobile foragers in the montane rainforests of eastern New Guinea beginning as early as the LGM. Growing archaeological evidence in the region suggests that the persistence of Late Pleistocene and Holocene foraging communities in montane rainforest environments was facilitated by their flexible use of diverse forest resources (2), and that resource use strategies differed by valley system (48). Cassowary exploitation presents a unique opportunity to investigate human management of a keystone rainforest species and the region’s largest vertebrate, whose feathers, meat, bone, and eggs are all highly valued by people today and may have been important to early foragers.

Evidence for hunting of cassowaries is limited. There is no evidence that foragers at Yuku hunted cassowaries, though they collected cassowary eggs, while some hunting of adults is evidenced at Kiowa in the Mid-Holocene. At Kiowa cassowary hunting does not appear to have been intensive given the relatively small assemblage and carcasses may have been initially processed offsite. Although screens were not used during the excavations, bones of small mammals were recovered (48), suggesting that taphonomy or human behavior may explain the absence of certain cassowary skeletal elements. The absence of wing and skull elements could be explained by taphonomy as these elements are less dense than the hind limb and pelvis and could more easily have been crushed and/or washed away. The lack of sternum, which is quite large and dense in cassowary, is less easily explained by taphonomic processes. In contemporary communities on eastern New Guinea, the sternum is often displayed on the outside of houses or hung inside in the thatch as hunting trophies, but we have no basis for inferring this practice in deeper time. Being a flightless bird with extremely reduced wings, the femur and tibiotarsus (the thigh and drumstick) of a cassowary would provide the most meat. Because Dwarf Cassowaries are quite heavy birds (15-25 kg)<sup>2</sup>, it is possible that carcasses were processed where they were caught (51) and only the meatiest parts (i.e. the hind limb) were brought to Kiowa.

Evidence for egg harvesting provides insights as to seasonality of foraging rounds and interactions between cassowary populations and people. Cassowaries are polyandrous with male parental care (Figure 7; 37). Female cassowaries mate and lay several clutches with several different males. Male cassowaries alone build nests of shallow depressions in the ground lined with leaves, incubate the 3-5 eggs for seven to eight weeks (~ 50 days), and then care for the chicks for up to nine months after hatching. Southern Cassowary (*Casuarius casuarius*) and Northern Cassowary (*Casuarius unappendiculatus*) breed from June-October, while Dwarf Cassowary (*Casuarius bennetti*) breed in some parts of New Guinea from February-April (52-

55). But seasonality varies across the island (56) and dwarf cassowary breeding seasonality is not narrowly predictable (57).

Field biologists report that nests are difficult to find, do not appear to be located in the same site each year, and tend to be located in closed understory (58). Males appear to leave the nest unattended for lengths of time during the laying stage, but once incubation begins, males do not leave the nest and remain predominantly inactive as they continuously incubate for ~50 days (58). Once the chicks hatch, males apparently do not remove the eggshell from the nest or consume the eggshell fragments (58). Cassowary chicks are precocial and leave the nest to follow the male within a few days of hatching (58). Male Dwarf Cassowaries at Crater Mountain, eastern New Guinea, appear to incubate in the fruiting lean season, rarely leaving the eggs, and females appear to shift altitudes at this time to track greater fruit availability (52).

The intersite pattern for hunting described above reverses with regard to egg harvesting. The eggshell assemblage from Kiowa is relatively small compared to that of Yuku, where egg harvesting begins in the LGM, and intensifies in the terminal Pleistocene and Early Holocene. No pattern of intensification of egg harvesting is discernible at Kiowa. Our expectation is that if people are using the rock shelters seasonally and/or are managing their exploitation of cassowary nests, then eggshell assemblages should exhibit patterns in the developmental stage of harvested eggs and incidences of eggshell burning. The two modeling approaches combined with the visual inspection of eggshell development confirm that a majority of eggs were harvested during later stages of ontogeny (Figure 4; S1.9-10). This pattern holds across both sites and through time, though the proportion of earlier stage eggs is slightly higher in the TP/EH at Kiowa. These data indicate that people at these two sites—and especially at Yuku—were preferentially harvesting eggs that contained chick embryos with fully formed limbs, beaks, claws and feathers (3, 59-61). Furthermore, while there is overall agreement between our two models and visual inspection in the identification of later stage eggshells, the 4-predictor model appears to be picking up further microstructural variation that allows us to improve the resolution of our identifications. Results of the 4-predictor model indicate that people were regularly collecting cassowary eggs in the very latest stage of embryonic development, only a few days prior to hatching. This pattern is most pronounced in the Late Pleistocene and Early Holocene and supports the possibilities that foragers were collecting eggshell from eggs that had already hatched, preferred consuming eggs with fully-formed embryos—considered a delicacy in some parts of the world—and/or that they were collecting eggs that they then allowed to hatch.

The correlation we found between incidences of eggshell burning and developmental stage is also noteworthy, particularly in terms of exterior burning (Table S 11). Early-stage eggs featured higher incidences of exterior burning than expected if burning and developmental stage were independent, whereas later stage eggs displayed lower incidences of burning than expected. This could indicate that early-stage eggs that contained primarily liquid contents (yolk and albumen)

were preferentially cooked intact over an open fire or in an earth oven. Interestingly, Majnep reports his people cooked eggs on *Ficus dammaropsis* leaves on hot rocks and specifically says other leaves were not strong enough (62). *F. dammaropsis* is currently a lower to mid montane taxon (850-2500 m asl). It is possible that the TP/EH habitat would not have supported *F. dammaropsis*, such that cooking in the eggshell would have been more prevalent, and the use of leaves (with less shell burning) became more common as treeline and montane vegetation moved up.

Eggshells assigned to the “Middle” stage by the 4-predictor model displayed a higher incidence of burning (both interior and exterior) than “Late” stage eggs, consistent with the possibility that some “Late” stage eggs were not cooked or consumed and were instead allowed to hatch (Figure 6). This pattern is visible both in the larger Yuku assemblage, and at Kiowa. At Kiowa, however, no eggshells assigned to the “Late” stage by the 4-predictor model display any signs of burning whatsoever.

The possibility that LP/EH foragers in montane New Guinea were hatching and rearing cassowary chicks is consistent with modern occurrences of cassowary chick rearing and translocation (63, 64), as well as a known history of plant and animal translocations in the region more broadly since the Late Pleistocene (65-67). These translocations primarily involved people trading or directly transporting tubers and medium-sized marsupials; however, Dwarf Cassowaries were imported prehistorically from New Guinea to New Britain, presumably as docile juveniles (Figure 7c; 63). These early forms of animal husbandry formed a component of wider niche construction practices in New Guinea’s tropical forests (68), that did not just involve the domestication of these spaces (69, 70) but also encouraged humans to attune their foraging strategies to these managed forest ecologies (71).

Although there is some evidence of a commensal relationship between early humans and rock doves possibly as early as 67 ka BP in Gibraltar (72), the data presented here may represent the earliest indication of human management of the breeding of an avian taxon anywhere in the world, preceding the early domestication of chicken (*Gallus gallus*) and geese (*Anser anser*) by several millennia (73, 74). This is particularly intriguing given the large size and behavioral characteristics of cassowary and other ratites generally—such as territoriality and aggression—that make them more surprising candidates for close interaction with humans, as compared to early avian domesticates, such as chickens and geese. However, cassowary chicks imprint readily to humans and are easy to maintain and raise up to adult size (Figure 1). Cassowary chicks are a traded commodity in parts of Papua New Guinea today (42).

Our findings highlight the importance of clarifying human interactions with keystone species, as these likely had ecological impacts at the landscape-scale. As important seed-dispersers, large K-reproducing ratites like cassowaries can be used as a deep-time proxy for human impacts on tropical forests. Research on modern cassowary populations in Australia indicates that their



reproductive ecology (e.g., substantial male parental investment and low annual productivity) makes them extremely sensitive to predation and habitat disturbance, and unlikely to successfully recolonize areas where they have previously been extirpated (58). Egg collecting at Kiowa and Yuku may have had more significant impacts on local cassowary populations compared to cassowary hunting. However, the persistence of cassowary eggshells in archaeological sites throughout montane New Guinea during the LGM to Early-Holocene (Table S 3) suggests that cassowaries—and rainforest biota more broadly—were relatively resilient to human exploitation and land use pressures of the time (Figure 1). Although forest clearance has occurred on New Guinea since the Pleistocene (75), there have always been large tracts of suitable forest habitat. Further research is needed to shed light on the co-evolutionary dynamics between people, cassowaries and New Guinea’s tropical forests, especially through the investigation of additional records of human-cassowary interaction paired with the study of long-term, high-resolution records of climate and vegetation change.

## **4. Materials and Methods**

### *4.1 Excavations*

Yuku was excavated in 1959 and Kiowa in 1960 by the late Susan Bulmer and local field assistants. The excavations produced a sequence replete with stone tools and flaking debitage, vertebrate faunal remains, and occasional bone tools, shells, exotic objects, and eggshell fragments. Excavation followed natural sedimentological boundaries, with each context being designated an archaeological level. Detailed description of the excavations, stratigraphy, AMS dating and materials analysis are presented in the Supplementary Information (Appendix S1).

### *4.2 Bone*

Vertebrate remains from Kiowa and Yuku were analyzed following established zooarchaeological standards and methods (76). Sorted materials were weighed and recorded according to size class and a full report of non-cassowary vertebrate remains is presented by Gaffney et al. (48). *Casuaris* spp. elements were identified using comparative skeleton collections housed in the Smithsonian’s National Museum of Natural History’s Bird Division.

### *4.3 Eggshell*

Eggshell fragments were weighed, measured and coded based on Munsell color guides. In addition, high-resolution scans of eggshell surfaces were collected using Keyence VK laser scanning microscope, and measurements of eggshell surface roughness were generated for analysis of eggshell developmental stage. Detailed methods of eggshell analysis, including predictive model parametrization, are presented in the Supplementary Information (Appendix S1.4-S1.9).

## **5. Acknowledgments and funding sources**

We wish to thank the late Dr. Susan Bulmer for her work in excavating and documenting the archaeological record of Kiowa and Yuku, and the Bulmer family for making the collection available for study. We thank the National Museum and Art Gallery of Papua New Guinea for granting ongoing loan of the material. Mr. Chris Milensky (Smithsonian, NMNH) assisted with the import of archaeological cassowary eggshell samples into the United States. We are indebted to David Bulmer for initial bulk faunal identifications and bagging undertaken in the 1980s, and to Francesca Galan and Andrew MacDougall for their assistance in recording basic measurements on the eggshell assemblage. We thank Anthony Sofia and Mark LaMarre of Keyence Corporation, and Matthew Wong, Daniel Chirchir and Steve Fontanini of Covalent Metrology for their assistance in generating high-resolution scans of eggshell. We are extremely grateful to Dr. Laurie Eccles (Penn State Anthropology) and Dr. Brendan Culleton (Penn State Energy and Environmental Sustainability Laboratories) for processing and analyzing radiocarbon samples for this project. We thank many people of the Pawai'ia and Gimi who shared their exceptional knowledge of hunting and cassowaries. We wish to thank the anonymous reviewers and editorial team for their time, efforts and generous feedback in reviewing the manuscript. Finally, we thank Dr. Patrick Roberts for inviting us to submit our paper for consideration in the Special Feature and for his work and the work of other colleagues in shedding light on the dynamic co-evolutionary relationships between people and tropical forests worldwide.

This work was supported by a Smithsonian National Museum of Natural History Peter Buck Postdoctoral Fellowship (KD). Further funding and support came from the Penn State College of the Liberal Arts and the Joyce L. and Douglas S. Sherwin Early Career Professorship in the Rock Ethics Institute.

## 6. References

1. Roberts P & Petraglia MD (2015) Pleistocene rainforests: barriers or attractive environments for early human foragers? *World Archaeology* 47(5):718–739.
2. Gaffney D & Denham T (2021) The Archaeology of Social Transformation in the New Guinea Highlands. in *The Oxford Handbook of the Archaeology of Indigenous Australia and New Guinea*, eds McNiven IJ & David B (Oxford University Press, Oxford, UK), p 41.
3. Douglass K, *et al.* (in review) Modeling avian eggshell microstructure to predict ontogenetic age and reveal patterns of human-avifauna interaction. *Journal of Archaeological Science*.
4. Kelly RL (2013) *The Lifeways of Hunter-Gatherers: The Foraging Spectrum* (Cambridge University Press, Cambridge, UK) 2nd revised edition Ed.
5. Kirch P & Hunt TL (1997) *Historical Ecology in the Pacific Islands: Prehistoric Environments and Landscape Change* (Yale University Press, New Haven) p 352.
6. Deur D, Dick A, Recalma-Clutesi K, & Turner NJ (2015) Kwakwaka'wakw "Clam Gardens". *Human Ecology* 43:201–212.

7. Armstrong CG, Dixon WM, & Turner NJ (2018) Management and Traditional Production of Beaked Hazelnut (k'áp'xw-az', *Corylus cornuta*; Betulaceae) in British Columbia. *Human Ecology* 46:547–559.
8. Rick TC, *et al.* (2016) Millennial-scale sustainability of the Chesapeake Bay Native American oyster fishery. *PNAS* 113(23):6568-6573.
9. Stephens L, *et al.* (2019) Archaeological assessment reveals Earth's early transformation through land use. *Science* 365(6456):897-902.
10. Winterhalder B & Lu F (1997) A Forager-Resource Population Ecology Model and Implications for Indigenous Conservation. *Conservation Biology* 11(6):1354-1364.
11. Roberts P, *et al.* (2020) Isotopic evidence for initial coastal colonization and subsequent diversification in the human occupation of Wallacea. *Nature Communications* 11(1).
12. Roberts P, *et al.* (2021) Reimagining the relationship between Gondwanan forests and Aboriginal land management in Australia's "Wet Tropics". *iScience* 24(3):102190.
13. Bliege Bird R, *et al.* (2020) Fire mosaics and habitat choice in nomadic foragers. *Proceedings of the National Academy of Sciences* 117(23):12904-12914.
14. Summerhayes GR, *et al.* (2010) Human adaptation and plant use in highland New Guinea 49,000 to 44,000 years ago. *Science* 330(6000):78-81.
15. Ford A (2017) Late Pleistocene lithic technology in the Ivane valley: A view from the rainforest. *Quaternary International* 448:31-43.
16. Summerhayes GR, Field JH, Shaw B, & Gaffney D (2017) The archaeology of forest exploitation and change in the tropics during the Pleistocene: The case of Northern Sahul (Pleistocene New Guinea). *Quaternary International* 448:14-30.
17. Walker D & Flenley J (1979) Late Quaternary Vegetational History of the Enga Province of Upland Papua New Guinea. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 286(1012):265-344.
18. Pedro N, *et al.* (2020) Papuan mitochondrial genomes and the settlement of Sahul. *Journal of Human Genetics* 65(10):875-887.
19. Bergström A, *et al.* (2017) A Neolithic expansion, but strong genetic structure, in the independent history of New Guinea. *Science* 357:1160-1163.
20. Haberle S (1993) Pleistocene vegetation change and early human occupation of a tropical mountainous environment. *Sahul in review: Pleistocene archaeology in Australia, New Guinea and Island Melanesia*, eds Frankhauser B & Spriggs M (Department of Prehistory, Australian National University, Canberra), pp 109-122.
21. Denham T (2018) *Tracing early agriculture in the highlands of New Guinea: plot, mound and ditch* (Routledge, London).
22. Roberts P, Gaffney D, Lee-Thorp J, & Summerhayes G (2017) Persistent tropical foraging in the highlands of terminal Pleistocene/Holocene New Guinea. *Nature Ecology & Evolution* 1:0044.
23. Gaffney D, Ford A, & Summerhayes GR (2015) Crossing the Pleistocene–Holocene transition in the New Guinea Highlands: Evidence from the lithic assemblage of Kiowa rockshelter. *Journal of Anthropological Archaeology* 39:223-246.
24. Hope G, Flannery T, & Boeari (1993) A preliminary report of changing Quaternary mammal faunas in subalpine New Guinea. *Quaternary Research*.
25. Mountain MJ (1991) Highland New Guinea hunter-gatherers: the evidence of Nombe Rockshelter, Simbu, with emphasis on the Pleistocene. PhD (Australian National University, Canberra, AU).

26. Field J, Fillios M, & Wroe S (2008) Chronological overlap between humans and megafauna in Sahul (Pleistocene Australia-New Guinea): a review of the evidence. *Earth-Science Reviews* 89(3-4):97-115.
27. Hope JH (1981) A new species of thylogale (Marsupialia; Macropodidae) from Mapala rock shelter, Jaya (Carstensz) Mountains, Irian Jaya (western New Guinea), Indonesia. *Records of the Australian Museum* 33(8):369-387.
28. Hope GS & Hope JH (1976) Man on Mt. Jaya. *The Equatorial Glaciers of New Guinea*, eds Hope GS, Peterson JA, Radok U, & Allison I (A.A. Balkema, Rotterdam), pp 225-240.
29. Sutton A, Mountain MJ, Aplin K, Bulmer S, & Denham T (2009) Archaeozoological records for the highlands of New Guinea: a review of current evidence. *Australian Archaeology* 69(1):41-58.
30. Bulmer R (1967) Why is the cassowary not a bird? A problem of zoological taxonomy among the Karam of the New Guinea Highlands. *Man* 2:5-25.
31. Bulmer RNH (1968) Strategies of Hunting in New Guinea. *Oceania* 38(4):302-318.
32. Rappaport RA (1984) *Pigs for the ancestors: Ritual in the ecology of a New Guinea people* (Yale University Press, New Haven, Connecticut).
33. Clarke SJ, Miller GH, Murray-Wallace CV, David B, & Pasveer JM (2007) The geochronological potential of isoleucine epimerisation in cassowary and megapode eggshells from archaeological sites. *Journal of Archaeological Science* 34(7):1051-1063.
34. Pasveer JM (2004) *The Djief Hunters, 26,000 Years of Rainforest Exploitation on the Bird's Head of Papua, Indonesia* (AA Balkema, Leiden).
35. Clarke SJ & Miller GH (2005) Isoleucine Epimerization in Casuarii Eggshells from Archaeological Sites in the Aru Islands, Liang Lemdubu and Liang Nabulei Lisa. *Archaeology of the Aru Islands, Eastern Indonesia*, Terra Australis, eds O'Connor S, Spriggs M, & Veth P (ANU Press, Canberra, AU), pp 295-306.
36. O'Connor S, *et al.* (2005) Liang Lemdubu, a Pleistocene cave site in the Aru Islands. *The Archaeology of the Aru Islands, Eastern Indonesia*, eds O'Connor S, Spriggs M, & Veth P (ANU Press, Canberra, AU), pp 171-204.
37. Winkler DW, Billerman SM, & Lovette IJ (2020) Cassowaries and Emu (Casuariidae). in *Birds of the World*, eds Billerman SM, Keeney BK, Rodewald PG, & Schulenberg TS (Cornell Lab of Ornithology, Ithaca, NY).
38. Mack AL & Wright DD (2005) The frugivore community and the fruiting plant flora in a New Guinea rainforest: identifying keystone frugivores. *Tropical fruits and frugivores: the search for strong interactors*, eds Dew JL & Boubli JP (Springer, The Netherlands), pp 184-203.
39. Bradford MG, Dennis AJ, & Westcott DA (2008) Diet and dietary preferences of the southern cassowary (*Casuarius casuarius*) in North Queensland, Australia. *Biotropica* 40(3):338-343.
40. Bradford MG & Westcott DA (2011) Predation of cassowary dispersed seeds: is the cassowary an effective disperser? *Integrative Zoology* 6(3):168-177.
41. Brodie FF & Pangau-Adam M (2017) Human impacts on two endemic cassowary species in Indonesian New Guinea. *Oryx* 51(2):354-360.
42. Johnson A, Bino R, & Igag P (2004) A preliminary evaluation of the sustainability of cassowary (Aves : Casuariidae) capture and trade in Papua New Guinea. *Animal Conservation* 7:129-137.

43. Steadman DW (2006) *Extinction and Biogeography of Tropical Pacific Birds* (University of Chicago Press, Chicago) pp 594-594.
44. Crowley BE (2010) A Refined Chronology Of Prehistoric Madagascar And The Demise Of The Megafauna. *Quaternary Science Reviews* 29(19-20):2591-2603.
45. Bulmer S (1975) Settlement and economy in prehistoric Papua New Guinea: a review of the archaeological evidence. *Journal de la Société des Océanistes* 31(46):7-75.
46. Gaffney D, Ford A, & Summerhayes GR (2016) Sue Bulmer's legacy in highland New Guinea: A re-examination of the Bulmer Collection and future directions. *Archaeology in Oceania* 51(S1):23-32.
47. Gaffney D, Summerhayes GR, Szabo K, & Koppel B (2019) The emergence of shell valuable exchange in the New Guinea Highlands. *American Anthropologist* 121(1):30-47.
48. Gaffney D, *et al.* (2021) Small game hunting in montane rainforests: Specialised capture and broad spectrum foraging in the Late Pleistocene to Holocene New Guinea Highlands. *Quaternary Science Reviews* 253:106742.
49. Wilkins J, *et al.* (2021) Innovative *Homo sapiens* behaviours 105,000 years ago in a wetter Kalahari. *Nature* 592:248-252.
50. Beacham BE & Durand SR (2007) Eggshell and the Archaeological Record: New Insights Into Turkey Husbandry in the American Southwest. *Journal of Archaeological Science* 34(10):1610-1621.
51. Whitehead H (2000) *Food rules: hunting, sharing, and tabooing game in Papua New Guinea* (University of Michigan Press, Ann Arbor) p 330.
52. Wright DD (2005) Diet, keystone resources and altitudinal movement of Dwarf Cassowaries in relation to fruiting phenology in a Papua New Guinean rainforest. *Tropical Fruits and Frugivores: the search for strong interactors*, eds Dew JL & Boubli JP (Springer, Netherlands), pp 201-236.
53. Folch A, Christie DA, Jutglar F, Garcia EFJ, & Sharpe CJ (2020) Dwarf Cassowary (*Casuarius bennetti*). in *Birds of the World version 1.0*, eds Hoyo Jd, Elliott A, Sargatal J, Christie DA, & Juana Ed (Cornell Lab of Ornithology, Ithaca, NY).
54. Folch A, Jutglar F, Garcia EFJ, & Sharpe CJ (2020) Northern Cassowary (*Casuarius unappendiculatus*). . in *Birds of the World version 1.0*, eds Hoyo Jd, Elliott A, Sargatal J, Christie DA, & E. de Juana (Cornell Lab of Ornithology, Ithaca, NY).
55. Folch A, Christie DA, Jutglar F, Garcia EFJ, & Sharpe CJ (2020) Southern Cassowary (*Casuarius casuarius*). in *Birds of the World version 1.0*, eds del Hoyo J, Elliott A, Sargatal J, Christie DA, & de Juana E (Cornell Lab of Ornithology, Ithaca, NY).
56. McAlpine JR, Keig G, & Falls R (1983) *Climate of Papua New Guinea* (CSIRO and Australia National University Press,, Canberra).
57. Coates B (1985) *The Birds of Papua New Guinea: Non-passerines* (Dove Publications, Alderley).
58. Bentrupperbaumer J (1997) Reciprocal ecosystem impact and behavioural interactions between cassowaries, *Casuarius casuarius*, and humans, *Homo sapiens*. Ph.D. (James Cook University, Townsville).
59. Brand Z (2012) Studies on Embryonic Development and Hatchability of Ostrich Eggs. PhD (University of Stellenbosch).
60. Brand Z, Cloete SW, Malecki IA, & Brown CR (2017) Ostrich (*Struthio camelus*) embryonic development from 7 to 42 days of incubation. *Br Poult Sci* 58(2):139-143.

61. Ar A & Gefen E (1998) Further improving hatchability in artificial incubation of ostrich eggs. *International Ratite Congress*, ed Huchzermeyer FW, pp 141-147.
62. Majnep IS & Bulmer R (1977) *Birds of My Kalam Country* (Auckland University Press, Auckland, NZ).
63. Healey CJ (1985) Pigs, cassowaries, and the gift of the flesh: a symbolid triad in Maring cosmology. *Ethnology* 24:153-165.
64. Sillitoe P (2003) *Managing animals in New Guinea: preying the game in the highlands* (Routledge, London, UK) p 416.
65. Heinsohn T (2003) Animal translocation: long-term human influences on the vertebrate zoogeography of Australasia (natural dispersal versus ethnophoresy). *Australian Zoologist* 32(3):351-376.
66. Fairbairn AS, Hope GS, & Summerhayes GR (2006) Pleistocene occupation of New Guinea's highland and subalpine environments. *World Archaeology* 38(3):371-386.
67. White JP (2004) Where the wild things are: prehistoric animal translocation in the circum New Guinea archipelago. *Voyages of Discovery: The Archaeology of Islands*, ed Fitzpatrick SM (Praeger Publishers, Westport, CT), pp 147-164.
68. Florin SA & Carah X (2018) Moving past the 'Neolithic problem': The development and interaction of subsistence systems across northern Sahul. *Quaternary International* 489:46-62.
69. Groube L (1989) The taming of the rain forests: a model for Late Pleistocene forest exploitation. *Foraging and Farming: The Evolution of Plant Exploitation*, eds Harris DR & Hillman GC (Routledge, London), pp 292-304.
70. Yen D (1989) The domestication of the environment. *Foraging and Farming: The Evolution of Plant Exploitation*, eds Harris DR & Hillman GC (Routledge, London), pp 55-75.
71. Kennedy J & Clarke WC (2004) Cultivated landscapes of the Southwest Pacific. in *Resource Management in Asia-Pacific Project* (Resource Management in Asia-Pacific Program (RMAP), Australian National University, Canberra).
72. Blasco R, *et al.* (2014) The earliest pigeon fanciers. *Scientific Reports* 4(5971).
73. Honka J, *et al.* (Over a Thousand Years of Evolutionary History of Domestic Geese from Russian Archaeological Sites, Analysed Using Ancient DNA. *Genes (Basel)* 9(7):367.
74. Wang MS, Thakur M, & Peng MS (2020) 863 genomes reveal the origin and domestication of chicken. *Cell Research* 30:693-701.
75. Haberle SG, Hope GS, & van der Kaars S (2001) Biomass burning in Indonesia and Papua New Guinea: natural and human induced fire events in the fossil records. *Palaeogeography, Paleoclimatology, Palaeoecology* 171:259-268.
76. Lyman RL (2005) Zooarchaeology. eds Maschner HDG & Chippendale C (AltaMira Press, Lanham), Volume 1 Ed, pp 835-870.
77. Carey C (1983) Structure and function of avian eggs. *Current Ornithology* 1:69-103.
78. O'Connor S, Aplin K, Pasveer J, & Hope G (2005) Liang Nabulei Lisa: a late Pleistocene and Holocene sequence from the Aru islands. *The Archaeology of the Aru Islands, Eastern Indonesia*, eds O'Connor S, Spriggs M, & Veth P (ANU Press, Canberra, AU), pp 125-161.
79. O'Connor S, *et al.* (2011) The power of paradigms: Examining the evidential basis for early to mid-Holocene pigs and pottery in Melanesia. *Journal of Pacific Archaeology* 2(2):1-25.

80. Aplin K (1981) Kamapuk fauna: A late Holocene vertebrate faunal sequence from the Western Highlands District, Papua New Guinea with implications for palaeoecology and archaeology. . B.A. Hons. Thesis (Austalian National University, Canberra).
81. White JP (1972) Ol Tumbuna: Archaeological Excavations in the Eastern Central Highlands, Papua New Guinea. (Australian National University, Dept. of Prehistory, Research School of Pacific Studies).
82. van der Kaars WA (1991) Palynology of eastern Indonesian marine piston-cores: a Late Quaternary vegetational and climatic record for Australasia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 85:239-302.
83. Bulmer S (1966) Pig bone from two archaeological sites in the New Guinea Highlands. *Journal of the Polynesian Society* 75:504-505.
84. Denham T (2016) Revisiting the past: Sue Bulmer's contribution to the archaeology of Papua New Guinea. *Archaeology of Oceania* 51(5e10).
85. Bulmer S (1960) Report on Archeological Field Work in the New Guinea Highlands (October 1959 to May 1960). (University of Auckland, Department of Anthroplogy).
86. Stuiver M & Polach H (1977) Discussion: Reporting of  $^{14}\text{C}$  Data. *Radiocarbon* 19:355-363.
87. Reimer P, *et al.* (2020) The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP). *Radiocarbon* 62(4):725-757.
88. Aver'yanova IO, Bogomolov DY, & Poroshin VV (2017) ISO 25178 standard for three-dimensional parametric assessment of surface texture. *Russian Engineering Research* 37:513-516.

## 7. Figures and Tables

### Figure and Table Legends

Fig 1: Human–cassowary interactions in highland Papua New Guinea (PNG): A) Endemic fruit forming key components of cassowary diet; B) hunters butchering a carcass of a Dwarf Cassowary (*C. bennetti*); C) man wearing headdress including cassowary feathers; D) juvenile cassowary (*C. bennetti*) being reared in a village in highland PNG; E) adult male cassowary (*C. bennetti*) in captivity in a village in highland PNG; F) man wearing a cassowary quill nose ornament and an armband with a cassowary bone dagger. Photo credits: A. Mack

Fig. 2: Simplified representation of eggshell microstructural changes during incubation as the cassowary embryo resorbs the calcium it requires for growth (>80%) from the surrounding eggshell (77). As a result of this process of resorption, the surface structure of eggshell mammillary cones changes during incubation, and measurements of surface texture can be used to estimate the ontogenetic age of the embryo (3): A) Male cassowary (*Casuaris casuaris*), as males incubate eggs and tend to chicks; B) green eggshell exterior (archaeological samples did not retain this green color; note that egg is not to scale); C) enlarged view of eggshell interior surface and mammillary cones; D-G) eggshell mammillary cones at “Early”, “Middle”, “Late” and hatched stages of development.

Fig 3: Maps of the study region, ecology and chronology of Late Pleistocene to Mid-Holocene sites with evidence of human–cassowary interaction. 1: Toé, with eggshell from 30–10 ka and bone from 30 ka to the Late Holocene (34); 2: Kria, with eggshell and bone from 7 or 6 ka to more recently (34); 3: Liang Nabulei Lisa, with eggshell from 16 ka to recently (78); 4: Liang Lemdubu, with eggshell from 20–1.5 ka or later, and bone from 20–1 ka (36); 5: Lachitu, with bone occurring sometime in the Mid-Holocene (79); 6: Kamapuk, with bone present about 5 ka but no later (80); 7: Nombe with eggshell from 20–0.2 ka and bone from possibly 36–0.2 ka (25); 8: Kafiavana, with eggshell >5 ka (81); 9: Aibura with cassowary eggshell and bone dating to either 3.8 ka or 0.7 ka (81); 10: Batari, with cassowary eggshell from 18–0.7 ka (81). Illustration: D. Gaffney; Inset A adapted from van der Kaars (82); Photos courtesy of D. Gaffney, A. Ford, and B. Shaw

Fig. 4: Overall proportions of the Kiowa and Yuku assemblages predicted to have been harvested at “Early”, “Middle”, and “Late” stages of ontogeny using the 1-predictor and 4-predictor models, and identified through visual assessment of cone microstructure erosion (CME) as having been harvested in the “pre-pitting” (equivalent to the “Early” stage in the predictive models) versus “pitting” stage (CME categories 2 and 3, equivalent to the later part of the “Middle” stage and to the “Late” stage in the predictive models), across chronological phases.

Fig. 5: Images rendered through high-resolution laser microscopy scanning of cassowary (*Casuarius* spp.) eggshell interior surfaces: A) sample displaying light weathering and clearly defined pitting of mammillary cones (sample ID 1249); B) sample displaying medium-light weathering and no pitting (pre-pitting stage; sample ID 1245); C) sample displaying extreme weathering. Diagnostic features too weathered to assess mammillary cone erosion stage (sample ID 1253). All examples derive from Yuku LP/EH layers.

Fig. 6: Density plot showing eggshell interior and exterior burning according to eggshell ontogenetic stage (1 = “Early”, 2 = “Middle”, and 3 = “Late”) prediction using the four-predictor model, and according to chronological phase at Kiowa and Yuku

Fig. 7: Cassowary reproductive ecology featuring male parental care: A) Male cassowary (*Casuarius casuarius*) sitting on the forest floor; B) Male cassowary (*Casuarius casuarius*) and two juveniles; C) young cassowary chick (*Casuarius* spp.)

Table 1: NISP, total and average sample surface area, and estimated MNI of Kiowa and Yuku cassowary eggshell assemblages. MNI is estimated by dividing total eggshell surface area (calculated using sample length and width measurements) by 264, which represents an estimate of the surface area of an intact dwarf cassowary egg.



## Figures and Tables

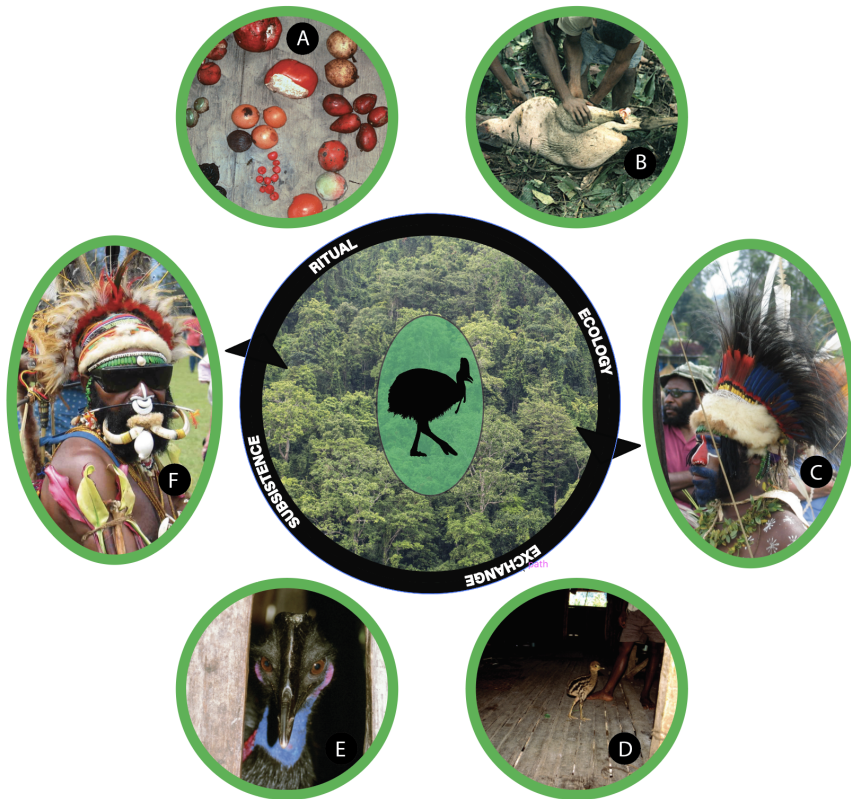


Figure 1: Human–cassowary interactions in highland Papua New Guinea: A) Endemic fruit forming key components of cassowary diet; B) hunters butchering a carcass of a Dwarf Cassowary (*C. bennetti*); C) man wearing headdress including cassowary feathers; D) juvenile cassowary (*C. bennetti*) being reared in a village in highland PNG; E) adult male cassowary (*C. bennetti*) in captivity in a village in highland PNG; F) man wearing a cassowary quill nose ornament and an armband with a cassowary bone dagger. Photo credits: A. Mack

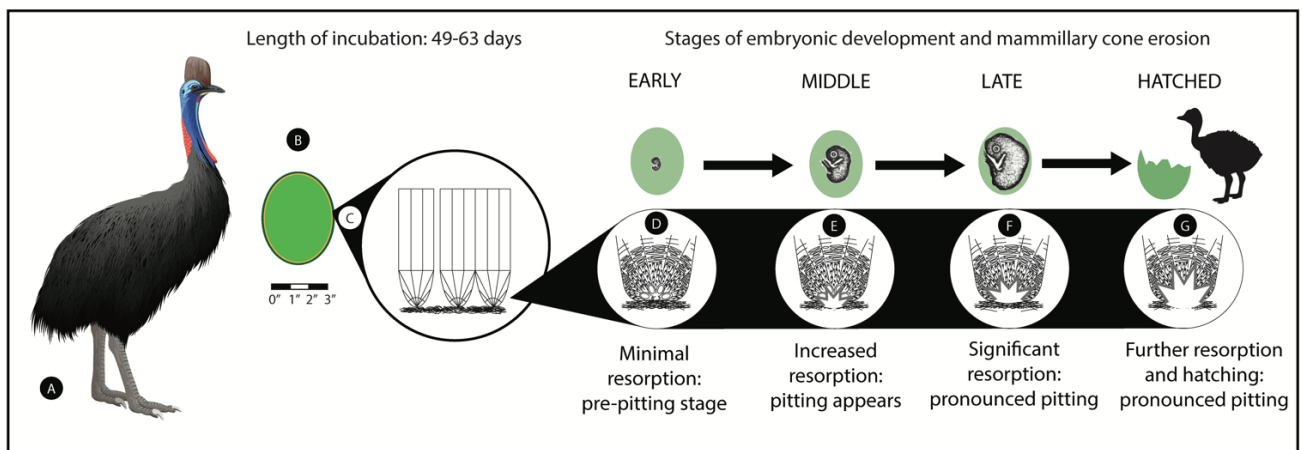


Figure 2: Simplified representation of eggshell microstructural changes during incubation as the cassowary embryo resorbs the calcium it requires for growth (>80%) from the surrounding eggshell (77). As a result of this process of resorption, the surface structure of eggshell mammillary cones changes during incubation, and measurements of surface texture can be used to estimate the ontogenetic age of the embryo (3): A) Male cassowary (*Casuaris casuaris*), as males incubate eggs and tend to chicks; B)

green eggshell exterior (archaeological samples did not retain this green color; note that egg is not to scale); C) enlarged view of eggshell interior surface and mammillary cones; D-G) eggshell mammillary cones at “Early”, “Middle”, “Late” and hatched stages of development.

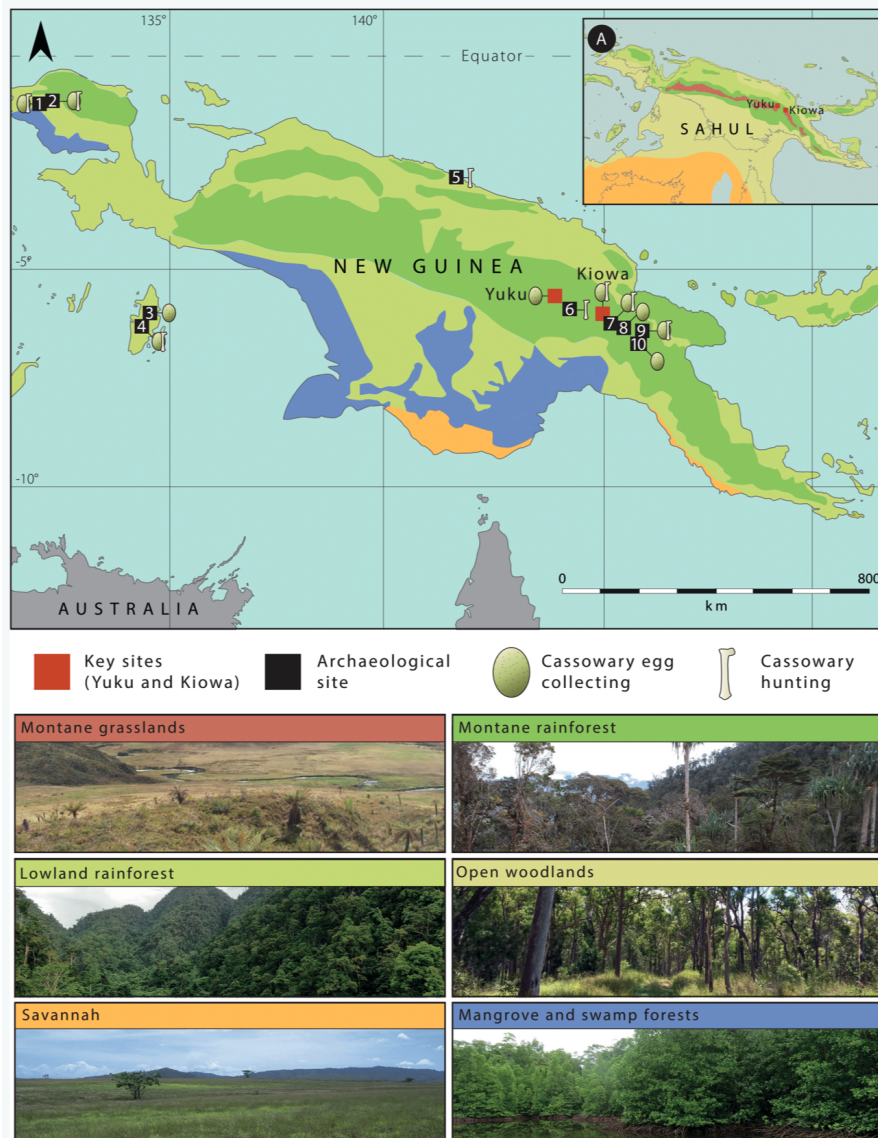


Figure 3: Maps of the study region, ecology and chronology of Late Pleistocene to Mid-Holocene sites with evidence of human–cassowary interaction. 1: Toé, with eggshell from 30–10 ka and bone from 30 ka to the Late Holocene (34); 2: Kria, with eggshell and bone from 7 or 6 ka to more recently (34); 3: Liang Nabulei Lisa, with eggshell from 16 ka to recently (78); 4: Liang Lemdubu, with eggshell from 20–1.5 ka or later, and bone from 20–1 ka (36); 5: Lachitu, with bone occurring sometime in the Mid-Holocene (79); 6: Kamapuk, with bone present about 5 ka but no later (80); 7: Nombe with eggshell from 20–0.2 ka and bone from possibly 36–0.2 ka (25); 8: Kafiavana, with eggshell >5 ka (81); 9: Aibura with cassowary eggshell and bone dating to either 3.8 ka or 0.7 ka (81); 10: Batari, with cassowary eggshell from 18–0.7 ka (81). Illustration: D. Gaffney; Inset A adapted from van der Kaars (82); Photos courtesy of D. Gaffney, A. Ford, and B. Shaw

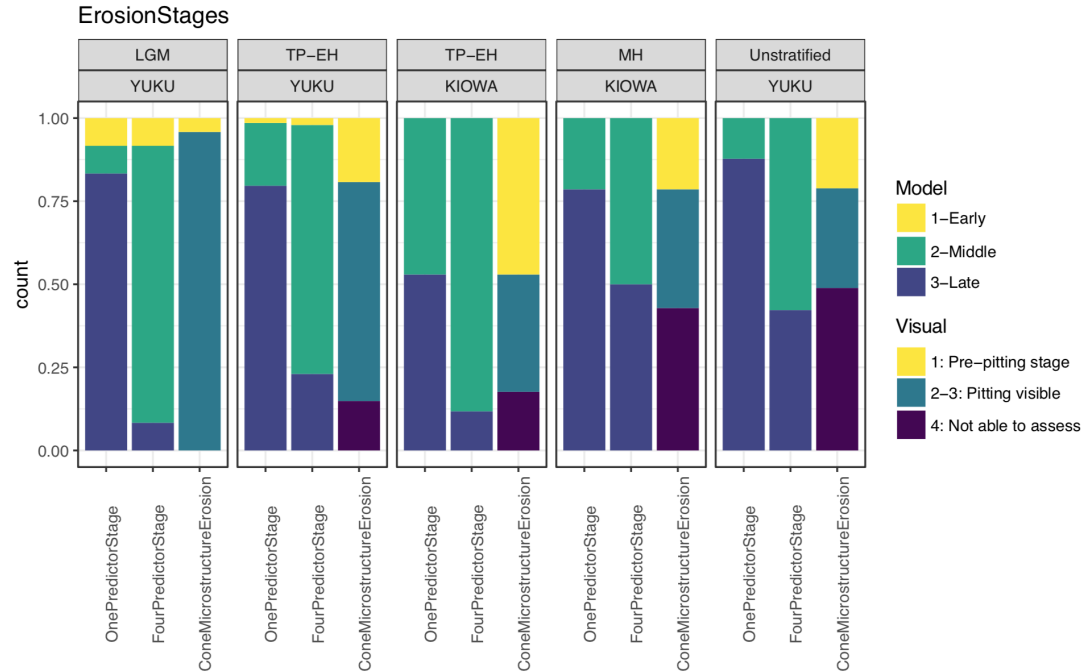


Figure 4: Overall proportions of the Kiowa and Yuku assemblages predicted to have been harvested at “Early”, “Middle”, and “Late” stages of ontogeny using the 1-predictor and 4-predictor models, and identified through visual assessment of cone microstructure erosion (CME) as having been harvested in the “pre-pitting” (equivalent to the “Early” stage in the predictive models) versus “pitting” stage (CME categories 2 and 3, equivalent to the later part of the “Middle” stage and to the “Late” stage in the predictive models), across chronological phases.

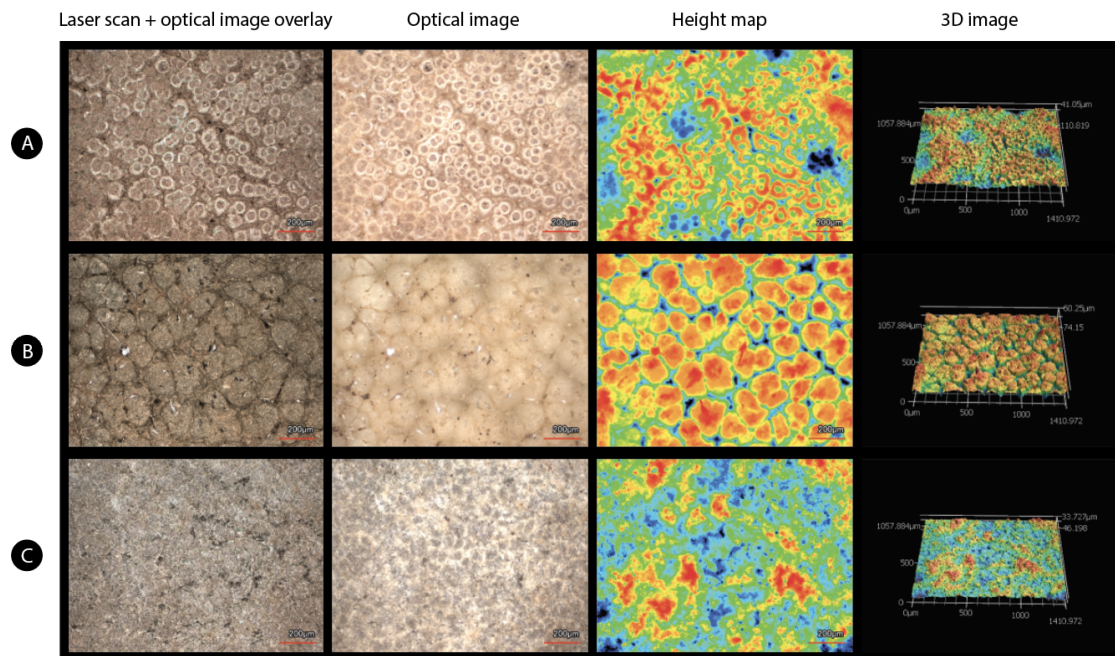


Figure 5: Images rendered through laser confocal microscopy scanning of cassowary (*Casuarius* spp.) eggshell interior surfaces: A) sample displaying light weathering and clearly defined pitting of mammillary cones (sample ID 1249); B) sample displaying medium-light weathering and no pitting (pre-

pitting stage; sample ID 1245); C) sample displaying extreme weathering. Diagnostic features too weathered to assess mammillary cone erosion stage (sample ID 1253). All examples derive from Yuku LP/EH layers.



Figure 6: Density plot showing eggshell interior and exterior burning according to eggshell ontogenetic stage (1 = “Early”, 2 = “Middle”, and 3 = “Late”) prediction using the four-predictor model, and according to chronological phase at Kiowa and Yuku



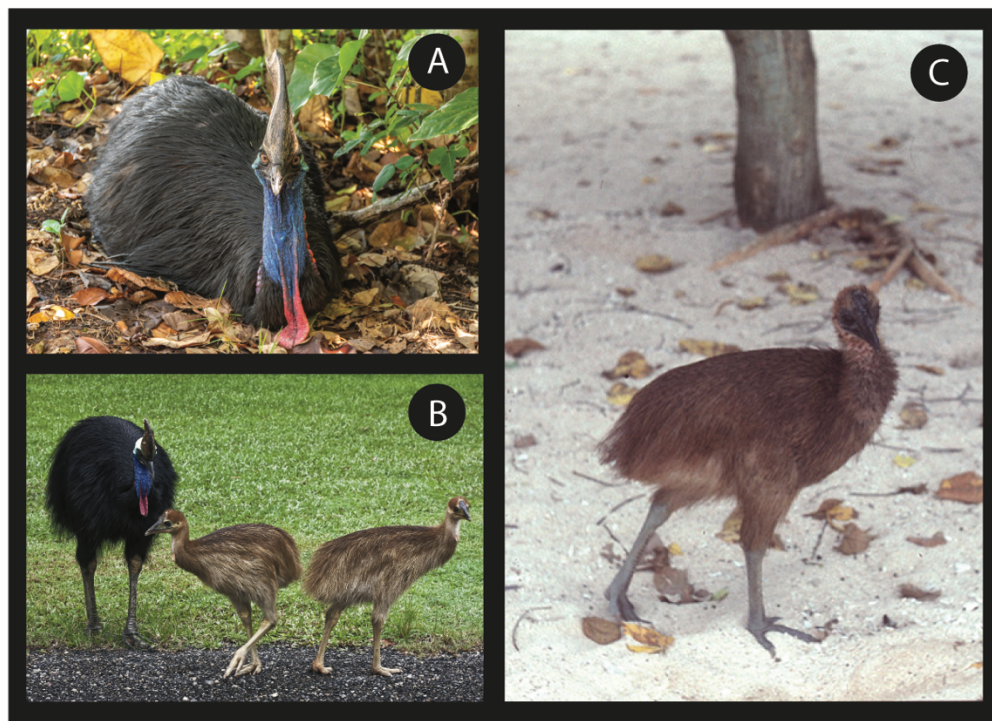


Figure 7: Cassowary reproductive ecology featuring male parental care: A) Male cassowary (*Casuarius casuarius*) sitting on the forest floor; B) Male cassowary (*Casuarius casuarius*) and two juveniles; C) young Dwarf Cassowary chick (*C. bennetti*) on New Britain in 1989 (Credit: G. Summerhayes)

Table 1: NISP, total and average sample surface area, and estimated MNI of Kiowa and Yuku cassowary eggshell assemblages. MNI is estimated by dividing total eggshell surface area (calculated using sample length and width measurements) by 264, which represents an estimate of the surface area of an intact dwarf cassowary egg.

|                                     | NISP       | Estimated total eggshell surface area in cm <sup>2</sup> | Average sample area in cm <sup>2</sup> | Estimated MNI |
|-------------------------------------|------------|--|--|---------------|
| <b>KIOWA</b>                        | <b>31</b>  | 746.93   | 24.09                                  | 2.83          |
| Terminal Pleistocene/Early Holocene | 17         | 374.09   | 22.01                                  | 1.41          |
| Mid-Holocene                        | 14         | 372.85   | 26.63                                  | 1.42          |
| <b>YUKU</b>                         | <b>988</b> | 25224.88   | 25.53                                  | 95.55         |
| Last Glacial Maximum                | 28         | 777.59   | 27.77                                  | 2.95          |
| Terminal Pleistocene/Early Holocene | 867        | 22504.93   | 25.96                                  | 85.25         |
| Unstratified                        | 93         | 1942.36  | 20.89                                  | 7.36          |



**Supplementary Information for**

**Late Pleistocene/Early Holocene sites in the montane forests of New Guinea yield early record of cassowary hunting and egg harvesting**

Kristina Douglass<sup>1,2,3\*</sup>, Dylan Gaffney<sup>4</sup>, Teresa J. Feo<sup>3,5</sup>, Priyangi Bulathsinhala<sup>6</sup>, Andrew L. Mack<sup>7</sup>, Megan Spitzer<sup>3</sup>, and Glenn R. Summerhayes<sup>8</sup>

<sup>1</sup>Department of Anthropology and Institutes for Energy and the Environment, The Pennsylvania State University, University Park, PA 16802

<sup>2</sup>Department of Anthropology, National Museum of Natural History, Smithsonian Institution, Washington, DC

<sup>3</sup>Department of Vertebrate Zoology, Division of Birds, National Museum of Natural History, Smithsonian Institution, Washington, DC

<sup>4</sup>Department of Archaeology, University of Cambridge, Cambridge, CB2 3DZ, United Kingdom

<sup>5</sup>California Council on Science and Technology, Sacramento, CA

<sup>6</sup>Department of Statistics, The Pennsylvania State University, University Park, PA

<sup>7</sup>Academic Affairs, The Pennsylvania State University, Altoona, PA 16601

<sup>8</sup>Archaeology Programme, School of Social Science, University of Otago, P.O. Box 56, Dunedin 9054

\*Corresponding author: Kristina Douglass; kdouglass@psu.edu

**This PDF file includes:**

- Detailed Materials and Methods
- Supplementary tables and figures

**Other supplementary materials for this manuscript include the following:**

- Dataset 1: Stratigraphic information, model probabilities, weathering and visual assessment of cone erosion, dimensions, color, and surface roughness measurements for all Cassowary eggshell samples from Kiowa and Yuku included in the study

## Supplementary Information Text

### S1. Materials and Methods

#### *S1.1: Excavations*

At Kiowa, the stratigraphy was relatively undisturbed down to the base of excavations at Level 12C, consisting of interleaved clay and ash lenses representing regular short-term occupation. Radiocarbon determinations were initially produced using conventional C14 dating of charcoal and bone (83) and these were later refined by two programs of AMS dating (48, 84). For the purposes of analysis in the present paper, Kiowa levels 2–6 are labelled Mid-Holocene, while levels 7–10 are Terminal Pleistocene and Early Holocene. At Yuku, the stratigraphy is more complex and there is evidence for disturbance in the upper levels as well as possible movement of small charcoal fragments down through the sequence. For this reason, Gaffney et al. (48) subdivided the archaeological levels into three analytical units: Analytical Unit 1 represents the upper levels 1–3 which reflects Mid-Late Holocene deposition, mixed due to burials and cooking pits being dug into the site; Analytical Unit 2 represents Terminal Pleistocene to Early Holocene occupation with possible movement of younger small remains down through the sediment matrix; Analytical Unit 3 represents Late Pleistocene occupation with no evidence for disturbance or intrusion. Like as Kiowa, the Yuku chronostratigraphy was initially produced using conventional dating on charcoal and later refined through two AMS programs (48, 84). For the analysis in the present paper, these Analytical Units were broadly retained: Yuku Level 6 and Crevice 2 (CR2) are labelled Last Glacial Maximum, and levels 3–5 and Crevice 1 (CR1) are labelled Terminal Pleistocene and Early Holocene. These divisions at Yuku should be considered as rough delineations; however, direct dating results suggests that all eggshell from the upper levels in Yuku (Level 3 in particular) are Terminal Pleistocene and Early Holocene specimens that have been redeposited by digging and burial activities. The full details of the excavations are detailed in Bulmer (83, 85) and Gaffney et al. (23, 48), and stratigraphic information for all of the eggshell samples is presented in Dataset 1.

All material including cassowary bone and eggshell was selected out by hand during excavation. Sieves were not used on site due to a lack of access to resources in the mid twentieth century. At Kiowa all cranial and mandibular material as well as worked bone, eggshell, and large bone fragments were kept for zooarchaeological analysis, but only two bags of small post cranial remains were retained due to transport difficulties. At Yuku all archaeological material was retained. The faunal and eggshell remains were bulk bagged by context and later sorted and tabulated by Bulmer at the University of Auckland. The collections were shifted to the University of Otago in 2013 and Gaffney later examined the samples under low power microscopy to assess their condition before sending to Douglass for further analysis.

#### *S1.2: $^{14}\text{C}$ Accelerator Mass Spectrometry (AMS) Dating*

Pretreatment and graphitization of the 25 eggshell samples took place in the Human Paleoecology and Isotope Geochemistry Laboratory at the Pennsylvania State University. Measurements were made on AMS housed at the Penn State Energy and Environmental Sustainability Laboratories. Radiocarbon

concentrations are given as fractions of the modern standard,  $D^{14}C$ , and conventional radiocarbon age, following the conventions of Stuiver and Polach (86). Sample preparation backgrounds were subtracted based on measurements of  $^{14}C$ -free calcite. All results were corrected for isotopic fractionation according to the conventions of Stuiver and Polach (86), with  $\delta^{13}C$  values measured on prepared graphite using the AMS. These can differ from  $\delta^{13}C$  of the original material, if fractionation occurred during sample graphitization or the AMS measurement, and are not shown. Dates were calibrated with OxCal 4.4. using IntCal2020 (87; See Table S1).

### *SI.3: Bone*

Vertebrate remains from Kiowa and Yuku were analyzed following established zooarchaeological standards and methods (76). Sorted materials were weighed and recorded according to size class and a full report of non-cassowary vertebrate remains is presented by Gaffney et al. (48). *Casuarius* spp. elements were identified using comparative skeleton collections housed in the Smithsonian's National Museum of Natural History's Bird Division.

### *SI.4: Eggshell sample preparation and analysis*

Eggshell fragments were gently rinsed in distilled water and left to air dry. Fragments were then weighed, measured (maximum length and width, and thickness), and assigned to taxon. Taxonomic identifications of cassowary eggshell were made using comparative egg collections in the Smithsonian's National Museum of Natural History's Bird Division. Cassowary eggs are much larger and thicker than any other bird eggs that might be found on New Guinea and have a distinctive exterior appearance. We are thus confident of our taxonomic identifications of cassowary eggshell to the genus level. A small number of eggshell fragments recorded at Kiowa and Yuku do not belong to the genus *Casuarius* and may be megapode eggs (*Megapodiidae* spp.). These were sorted and bagged according to context and are not included in the analyses presented in this paper, with the exception of two radiocarbon determinations (Table S1).

All cassowary eggshell was given a color code based on the Munsell soil color chart (interior and exterior portions). Preliminary taphonomic assessments of weathering, interior and exterior burning, chipping and flaking of eggshell surfaces, the presence of plant matter and/or mineral concretions were recorded. The range of Munsell color values indicative of burning was compiled and used for further analysis of the relationship between incidences of burning and eggshell developmental stage (see Fig. 11).

Eggshell surface area was roughly estimated with the formula linked below—based on measurements taken on intact eggs in modern comparative collections—and used to generate estimates of the Minimum Number of Individual eggs in the assemblage (MNI):

<https://goodcalculators.com/egg-surface-area-and-volume-calculator/>

### *SI.5: Laser scanning confocal microscopy*



High-resolution scans of all identified archaeological cassowary eggshell fragments were acquired, in order to evaluate changes in eggshell microstructural features associated with ontogeny (3, 50). We also acquired scans of three samples of modern cassowary eggshell (*Casuaris* spp.) of unknown ontogenetic age that we used for qualitative purposes to inform our visual assessments of archaeological specimens. Scans were acquired using a Keyence VK-X1100 (violet) 3D laser scanning microscope at 10X magnification (n=1019). Auto mode, which automatically determines the Z range of the sample as well as the necessary laser intensity, was used to collect the data. The average Z range was 0.5nm and the average XY range was 130 nm. Scans have a lateral resolution of ca. 741 nm. The raw data were then processed using the VK-X1100 software. The surface shape correction tool was applied to normalize the surface, to reduce variation caused by the differential curvature of each sample. Surface roughness measurements—Sa, Sz, Ssk, Sku—were generated using the area roughness tool in the VK-X1100 software (See S1.6 for description of surface roughness parameters).

#### *S1.6: Description of 3D areal surface texture parameters used in the study*

The following four 3D areal surface texture parameters defined by the International Organization for Standardization (ISO 25178) were used. All four relate to changes in the height values of eggshell microstructures along the z-axis of eggshell surfaces (88).

##### 1) Sa – arithmetic mean height of the surface:

Sa is the extension of Ra (arithmetical mean height of a line) to a surface. It expresses, as an absolute value, the difference in height of each point compared to the arithmetical mean of the surface.

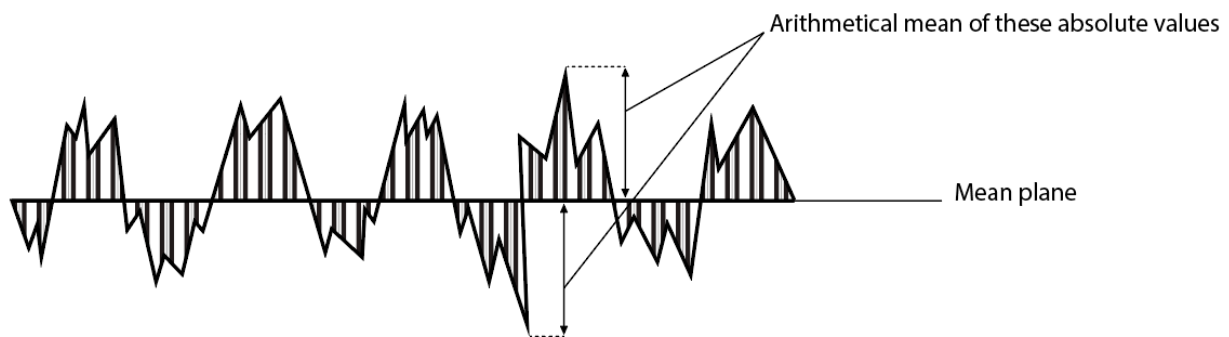


Fig. S 1: Example of Sa. In reality Sa is an areal surface parameter, so that the mean plane is not a line, but an area.

##### 2) Sku – kurtosis of height distribution:

Sku value is a measure of the sharpness of the roughness profile (88).

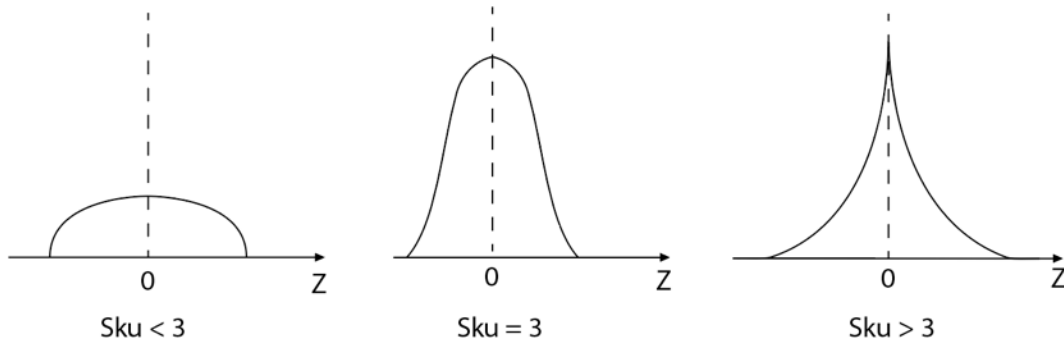


Fig. S 2: Examples of  $S_{ku}$ .  $S_{ku} < 3$ : height distribution is skewed above the mean plane;  $S_{ku} = 3$ : height distribution is normal (e.g. Sharp portions and indented portions co-exist);  $S_{ku} > 3$ : height distribution is spiked.

### 3) $S_{sk}$ – skewness of height distribution:

$S_{sk}$  values represent the degree of bias of the roughness shape (88).

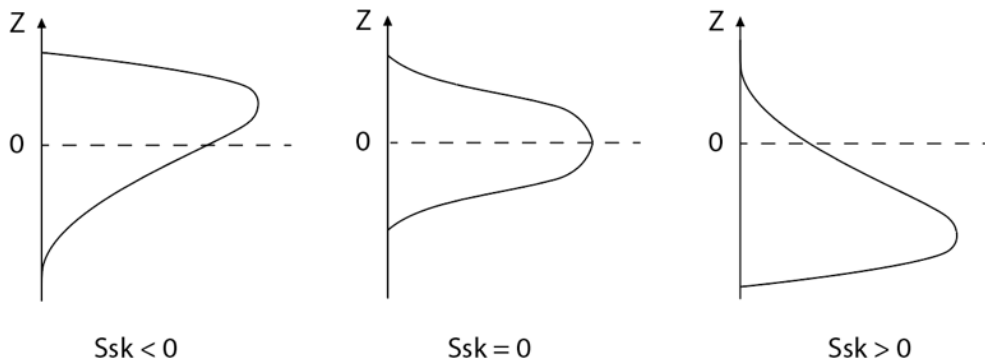


Fig. S 3: Examples of  $S_{sk}$ .  $S_{sk} < 0$ : height distribution is skewed above the mean plane;  $S_{sk} = 0$ : height distribution (peaks and pits) is symmetrical around the mean plane; and  $S_{sk} > 0$ : height distribution is skewed below the mean plane.

### 4) $S_z$ – maximum height of the surface:

$S_z$  is defined as the sum of the largest peak height value ( $S_p$ ) and the largest pit depth value ( $S_v$ ) within the defined area (88).

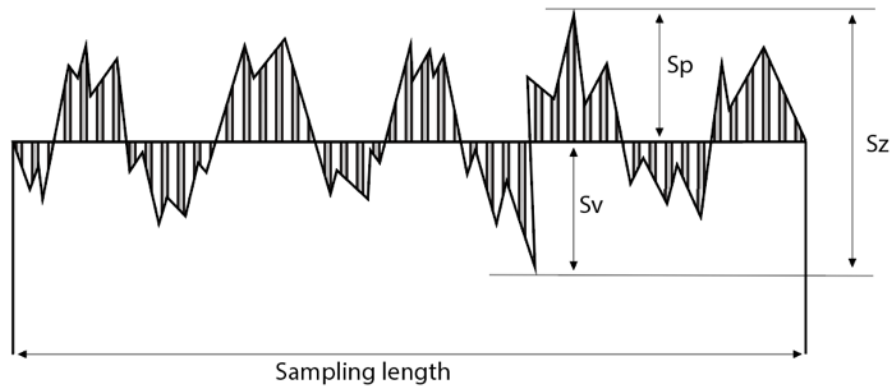


Fig. S 4: Example of  $S_z$  visualized along a profile line. In reality  $S_z$  is an areal surface parameter, so that the sampling length would in fact be the sampling area.

#### *SI.7: Predictive modeling*

Surface roughness measurements ( $S_a$ ,  $S_z$ ,  $S_{sk}$ ,  $S_{ku}$ ) taken of the interior portion of each eggshell were run through two predictive models we developed using a comparative series of ostrich eggshell. We generated predictions of ontogenetic age using both our 1-predictor model, which considers  $S_a$  (arithmetic mean height) roughness values, and our 4-predictor model, which considers  $S_a$ ,  $S_{ku}$  (kurtosis),  $S_{sk}$  (skewness), and  $S_z$  (maximum height). We generated predictions of ontogenetic age for each eggshell fragment in the assemblage with each model, excluding eggshells that were categorized as extremely weathered ( $n=53$ ; see Table 2).

In the model set-up, based on the length of days of incubation for ostrich, the outcome is the number of days from the time an egg was laid (day 1) until the egg hatched (day 42), or was harvested prior to hatching and broken open for consumption (days 1-41). Prior to developing our statistical models, we discretized the outcome variable (days to sampling or hatching) as “Early” (from day 1 to day 21), “Middle” (from day 22 to 35) and “Late” (day 36 to 42). These three stages were established based on detailed observations of embryonic growth in ostriches (3, 60).

#### *SI.8: Comparability of ostrich time series to archaeological cassowary assemblage*

We previously tested the predictive models on emu (*Dromaius novaehollandiae*) eggshell of known ontogenetic age and found them to be applicable to the analysis of eggshell of other ratites with similar lengths of incubation to ostrich (3). As emu and cassowary are members of the same family (Casuariidae), and are of comparable size, we feel confident in applying the models to cassowary eggshell (Fig. S5).

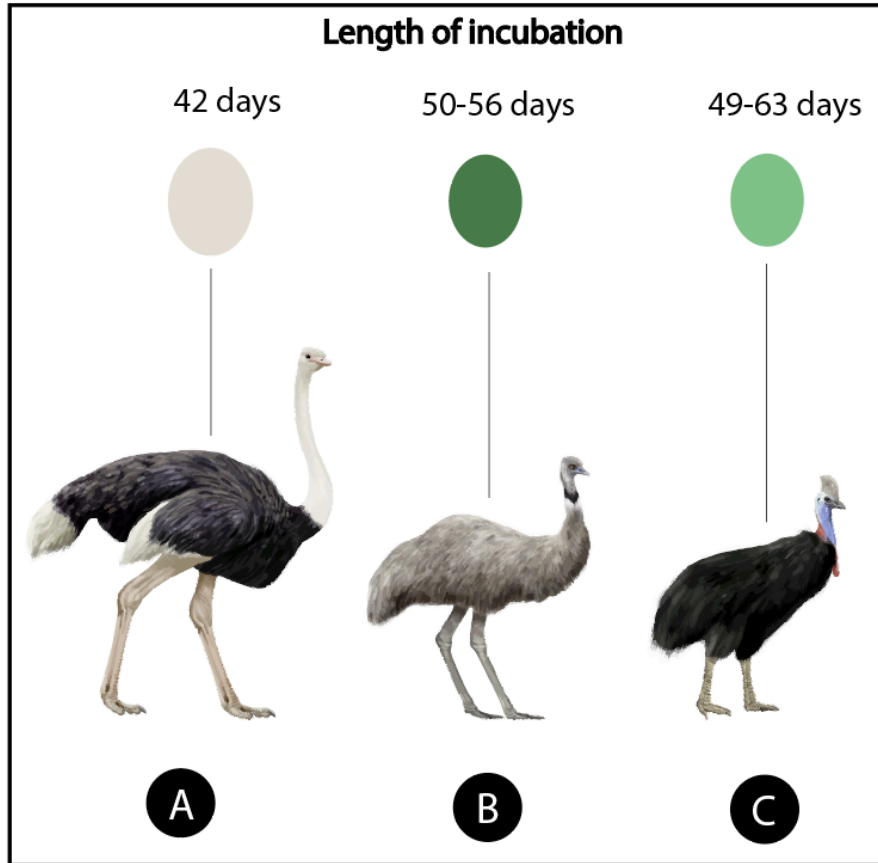


Fig. S 5: Incubation duration of three ratite species relevant to the modeling in this study: A) Common Ostrich (*Struthio camelus*)—a comparative series of ostrich eggshell representing every day of incubation was used to develop the predictive models; B) Emu (*Dromaius novaehollandiae*)—emu eggshells of known ontogenetic age were used to test the models' applicability to other ratite species; C) Southern Cassowary (*Casuarius casuarius*)—this paper applies the models to the analysis of archaeological cassowary eggshell.

We also compared the frequency distributions of surface roughness values from the ostrich time series and cassowary assemblage. These comparisons (Figs. S6-S9) indicate that the ranges of roughness values of the ostrich and cassowary eggshells overlap sufficiently to justify applying the predictive models to the archaeological assemblage.

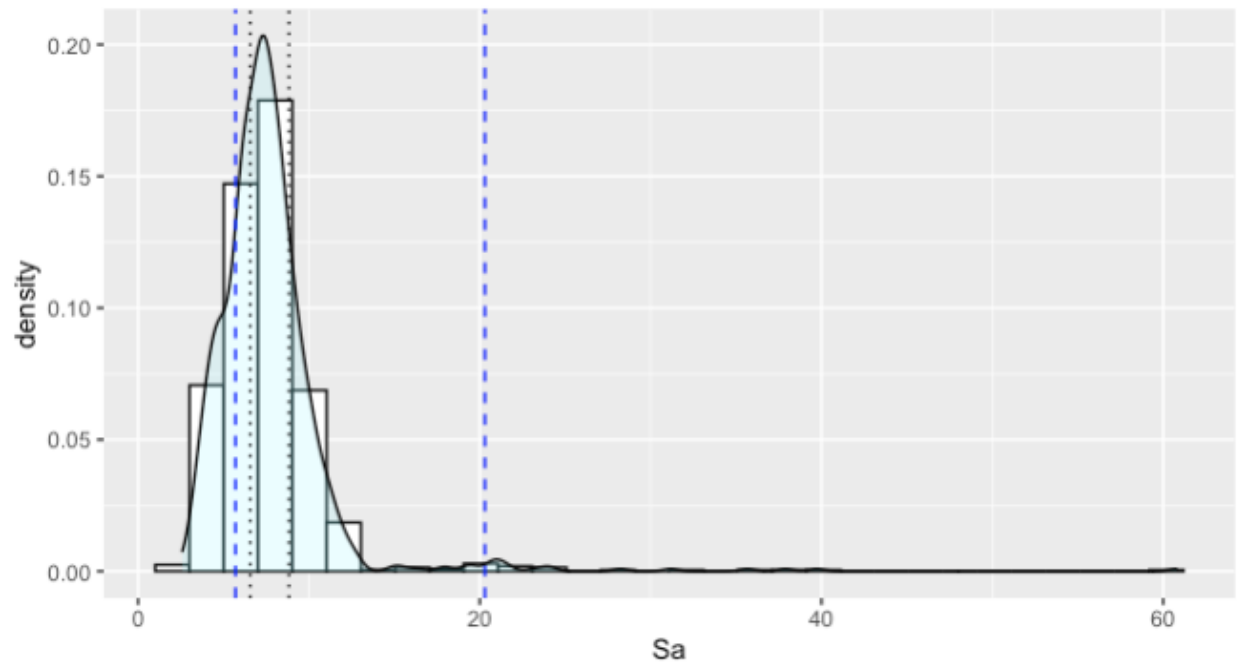


Fig. S 6: Frequency distribution of Sa values (arithmetic mean height of the surface) for cassowary assemblage. The blue dashed lines indicate the range of Sa values from the ostrich comparative sample (3) and the black dotted lines indicate the range of Sa values measured on 3 modern cassowary eggshell samples of unknown ontogenetic age. The distribution reflects an overall reduced difference in the heights of peaks and pits in relation to the mean plane, as compared to ostrich. This could be a factor of taphonomic weathering, since these are archaeological samples, and/or morphological differences between cassowary and ostrich eggs.

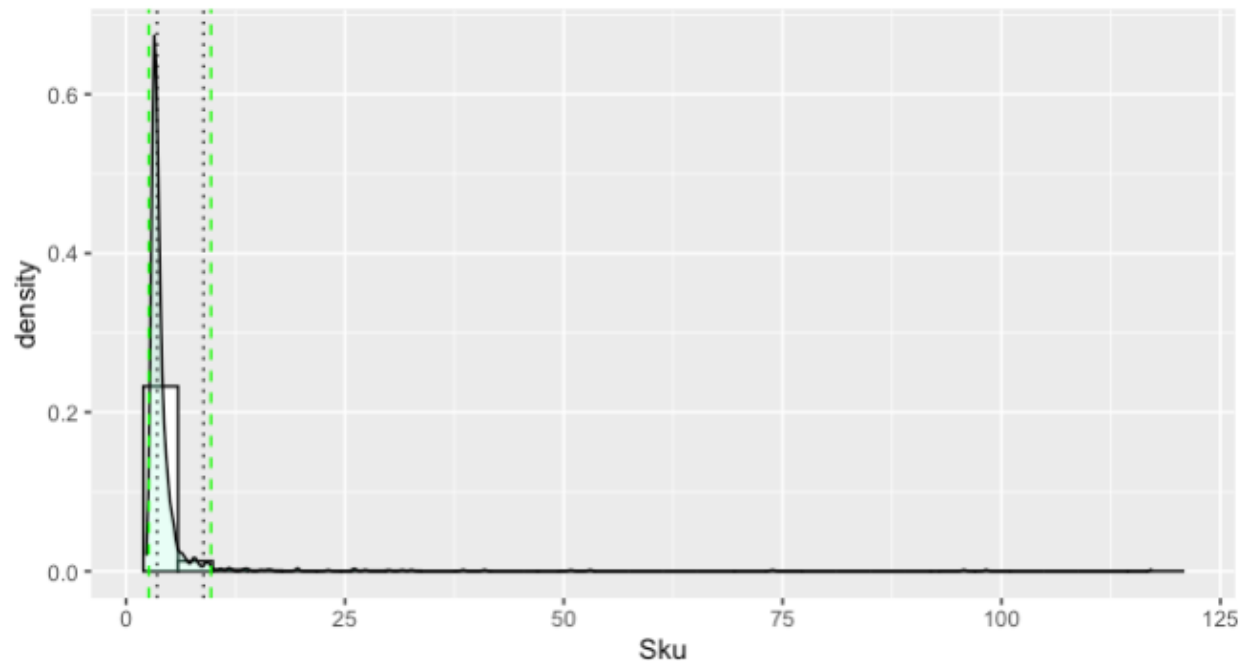


Fig. S 7: Frequency distribution of Sku values (kurtosis of the height distribution) for cassowary assemblage. The green dashed lines indicate the range of Sku values from the ostrich comparative sample (3) and the black dotted lines indicate the range of Sku values measured on 3 modern cassowary eggshell samples of unknown ontogenetic age. The distribution reflects overall reduced Sku values as compared to ostrich. Like the ostrich sample, the mean Sku values are greater than 3 indicating that the height distribution is spiked (sharp/pointy). The lower values as compared to ostrich could be a factor of taphonomic weathering, which may have abraded and smoothed the sharpness of the features.

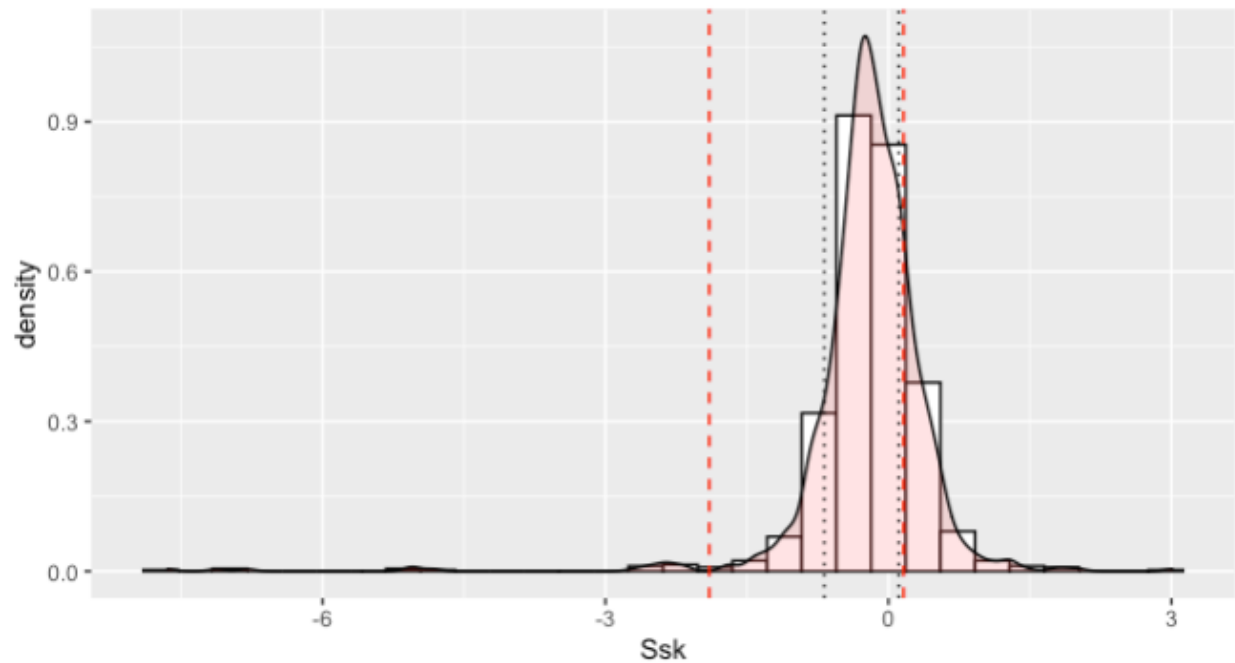


Fig. S 8: Frequency distribution of Ssk values (skewness of the height distribution) for cassowary assemblage. The red dashed lines indicate the range of Ssk values from the ostrich comparative sample (3) and the black dotted lines indicate the range of Ssk values measured on 3 modern cassowary eggshell samples of unknown ontogenetic age. The distribution reflects overall higher Ssk as compared to ostrich. This indicates that the cassowary assemblage height distributions (peaks and pits) are approximately symmetrical around the mean plane ( $Ssk=0$ ), whereas the ostrich comparative sample exhibits height distributions skewed above the mean plane ( $Ssk<0$ ). This could be a factor of taphonomic weathering, since these are archaeological samples.

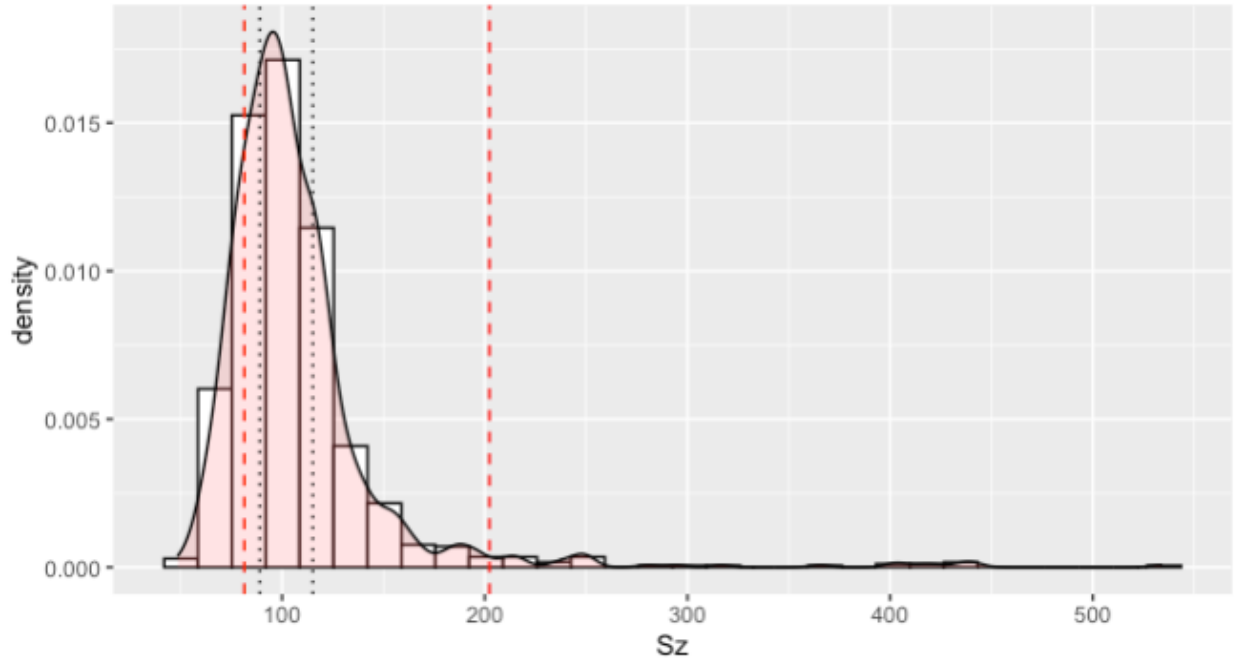


Fig. S 9: Frequency distribution of Sz values (maximum height of the surface) for cassowary assemblage. The red dashed lines indicate the range of Sz values from the ostrich comparative sample (3) and the black dotted lines indicate the range of Sz values measured on 3 modern cassowary eggshell samples of unknown ontogenetic age. The distribution reflects overall reduced height values as compared to ostrich. This could be a factor of taphonomic weathering, since these are archaeological samples, and/or morphological differences between cassowary and ostrich eggs.

#### SI.9: Notation and model setup

Our models were trained on surface texture measurements taken from a set of 2 ostrich eggs (*Struthio camelus*) for each of the 42 days of ostrich embryonic development ( $n=84$  individual eggs). The model was then tested on surface texture measurements derived from ostrich eggs representing each day of development ( $n=42$  individual eggs). This modern ostrich comparative developmental series is described in detail in Douglass et al. (3). To assess the reliability of the model predictions when moving from the modern ostrich developmental series to archaeological samples, we conducted a sensitivity analysis by adding varying degrees of noise to the surface texture measurements, as a proxy for the effects of taphonomic weathering (3). Model classification accuracy for the 1-predictor model was 100% for “Early”, 50% for “Middle” and 57% for “Late” stages. For the 4-predictor model classification accuracy was 100% for “Early”, 36% for “Middle” and 71% for “Late” stages.

Our predictive models are described using the following notation:  $Y$  is the ordered response with  $J$  categories.  $P(Y \leq j|\mathbf{x})$  is the probability that  $Y$  is less than or equal to the  $j^{th}$  category for a given value of  $\mathbf{x}$ , in which  $\mathbf{x}$  represents the predictor variables in the model. The odds of the response being less than or equal to a particular category is defined as



$$\frac{P(Y \leq j|\mathbf{x})}{P(Y > j|\mathbf{x})}$$

Then the cumulative log odds are defined as

$$\text{logit}(P(Y \leq j|\mathbf{x})) = \log\left(\frac{P(Y \leq j|\mathbf{x})}{P(Y > j|\mathbf{x})}\right) = \log\left(\frac{P(Y \leq j|\mathbf{x})}{1 - P(Y \leq j|\mathbf{x})}\right), j = 1, 2, \dots, J - 1$$

We modeled the cumulative log odds as a function of the explanatory variables through a cumulative logit model. In particular, the cumulative logit model for these data is written as

$$\log\left(\frac{P(Y \leq j)}{P(Y > j)}\right) = \alpha_j + \boldsymbol{\beta}^T \mathbf{x}, j = 1, 2, \dots, J - 1.$$

In the above model,

- $Y = \begin{cases} 1 & \text{if sampled during the early stage (days 1 – 21)} \\ 2 & \text{if sampled during the middle stage (days 22 – 35)} \\ 3 & \text{if sampled during the late stage (days 36 – 42)} \end{cases}$
- $J = 3$  for three categories of the response: early, middle and late.
- $\log\left(\frac{P(Y \leq j|\mathbf{x})}{P(Y > j|\mathbf{x})}\right)$  is the log odds of an egg being sampled at a certain stage or earlier for a given value of the predictor variable(s)
- $\alpha_j$  is the intercept for each cumulative logit
- $\boldsymbol{\beta} = (\beta_1, \beta_2, \dots, \beta_p)^T$  is a vector of regression coefficients corresponding to the roughness measurements

Parameter estimates and the standard errors are estimated using the *plor* package in *R*.

The one-predictor model (using Sa as a variable) can be written as

*Equation 1*

$$\begin{aligned} \text{logit}\left(\hat{P}(Y \leq 1)\right) &= -7.44 + 0.54Sa \\ \text{logit}\left(\hat{P}(Y \leq 2)\right) &= -4.71 + 0.54Sa \end{aligned}$$

Then the model parameters are interpreted as:

- For every unit increase in Sa, the odds of an egg being sampled during the early stage of its incubation (as opposed to middle or late stages) is expected to increase by 71.6% ( $e^{0.54}=1.716$ )
- The odds of an egg being sampled during the early stage (as opposed to middle or late stages) is expected to be 0.0006 ( $e^{-7.44}=0.0006$ ) when Sa is equal to zero

- The odds of being sampled during the early or middle stages (as opposed to late stage) is expected to be 0.009 ( $e^{-4.71}=0.009$ ) when Sa is equal to zero

The numerical values we obtained for the model parameter estimates agree with our initial observations of the relationship between eggshell ontogenetic age and the Sa roughness measurement.

The four-predictor model (using Sa, Sku, Ssk, Sz) can be written as

*Equation 2*

$$\text{logit}(\hat{P}(Y \leq 1)) = -4.57 + 0.40Sa - 0.10Sku + 1.17Ssk + 2.14 \times 10^{-5}Sz$$

$$\text{logit}(\hat{P}(Y \leq 2)) = -1.64 + 0.40Sa - 0.10Sku + 1.17Ssk + 2.14 \times 10^{-5}Sz$$

### *SI.10: Visual Assessment*

Visual assessment of weathering and microstructural features for each cassowary eggshell sample in the assemblage (n=1019) was conducted using a set of 4 high-resolution images (see Fig. 9) and 4 cross-sectional profiles derived from each cassowary eggshell fragment in the assemblage (see Fig. 10; n=8152 total visualizations) and generated by the Keyence VK-X1100 (violet) 3D laser scanning microscope. We categorized each sample according to the degree of weathering as follows:

- 1: Light; features clearly defined
- 2: Medium-Light; features clearly defined in some areas
- 3: Medium-Extreme; features distinguishable but extremely weathered
- 4: Extreme; features not visible

We then recorded the degree of mammillary cone microstructure erosion (CME) by assessing whether pitting was visible, or whether diagnostic features were too weathered to permit confident assessment as follows:

- 1: Pre-pitting stage
- 2: Pitting visible
- 3: Pitting visible; diagnostic features weathered
- 4: Features too weathered to distinguish erosion stage

Our selection of pitting as a key diagnostic feature is based on our morphological study of Ostrich CME over the course of embryonic development, which confirms that the presence of pitting is indicative of eggs with embryos in the late “Middle” and “Late” stages of development. Eggs with pitting contain chick embryos with fully formed beaks, feathers, wings, limbs, and claws, and by this stage the embryo outweighs the remaining yolk and albumen in the egg (3, 60). Samples identified as weathering category 4 were not included in the statistical modeling of eggshell stage and could not be assessed as to the presence of pitting.

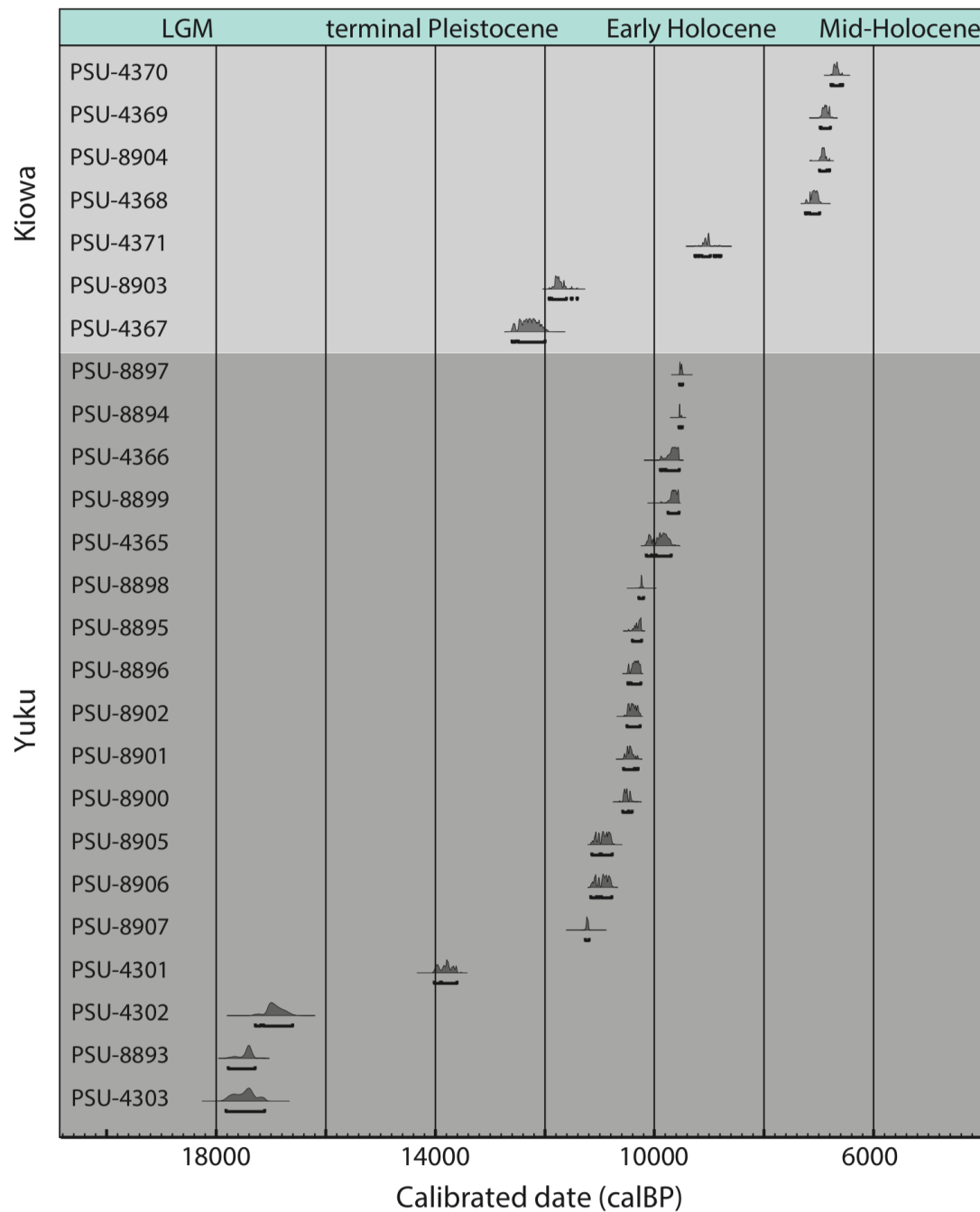


Fig. S 10: Calibrated radiocarbon determinations on avian eggshell from Yuku and Kiowa. Calibrated with OxCal 4.4. using IntCal2020 (87).

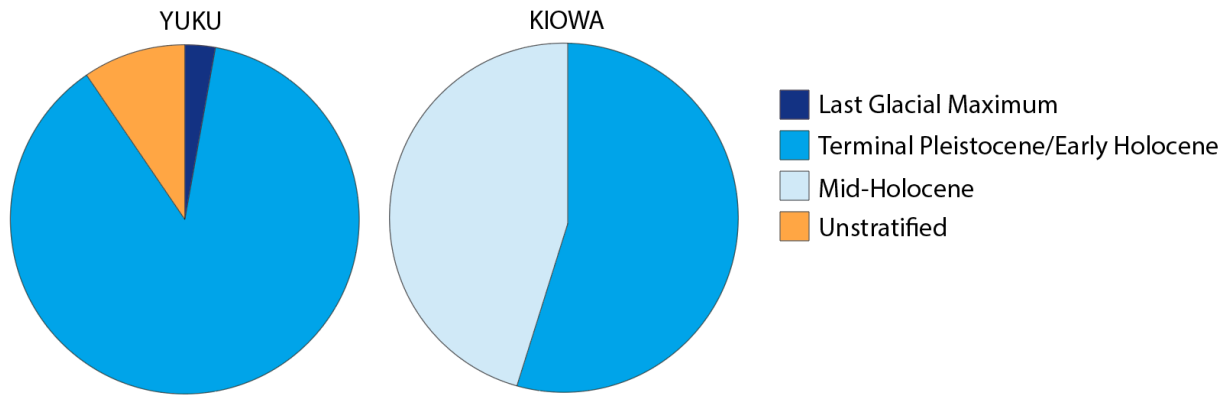


Fig. S 11: Proportions of Kiowa (n=31) and Yuku (n=988) eggshell assemblages relative to chronological phase.

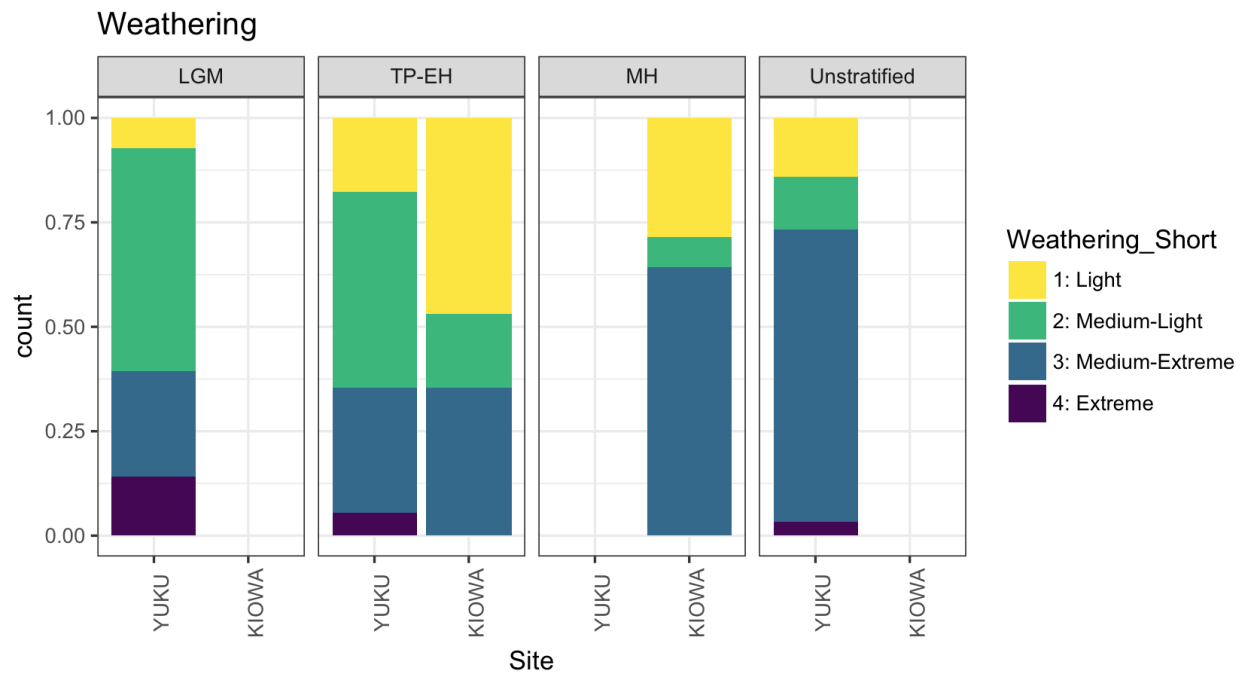


Fig. S 12: Proportions of samples with different degrees of weathering in Kiowa and Yuku assemblages across chronological phases

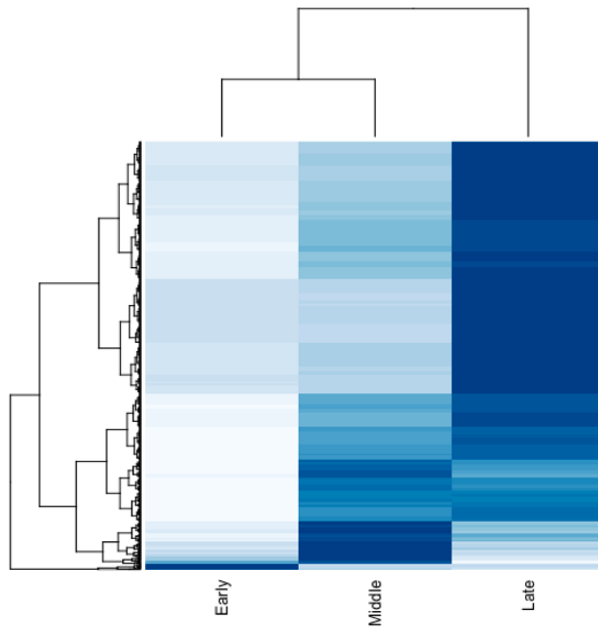


Fig. S 13: Predicted probabilities of eggshell developmental stage (“Early”, “Middle”, “Late”) using the 1-predictor model. Color intensities reflect the magnitude of the predicted probability values. Branches on the left indicate clustering of the samples based on the similarity of their estimated probabilities. Branches along the top of the plot indicate clustering of the stages, showing that the “early” stage predicted probabilities across a majority of the eggshells are more similar to the “middle” stage probabilities than to those of the “late” stage.

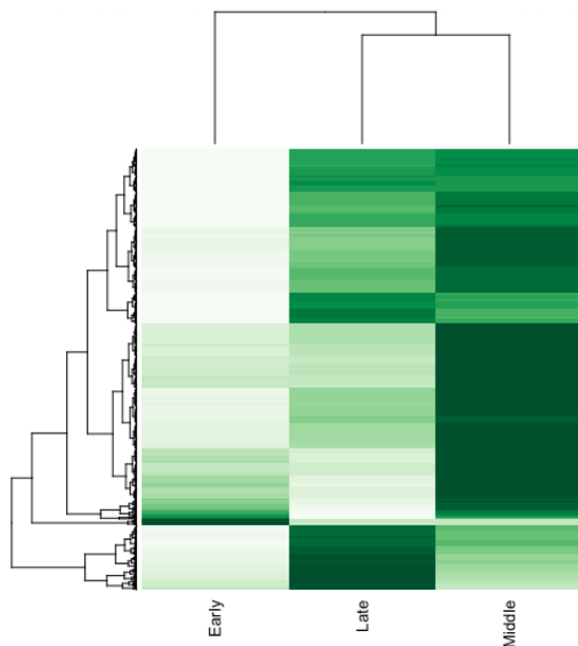


Fig. S 14: Predicted probabilities of eggshell developmental stage (“Early”, “Middle”, “Late”) using the 4-predictor model. Color intensities reflect the magnitude of the predicted probability values. Branches on the left indicate clustering of the samples based on the similarity of their estimated probabilities. Branches along the top of the plot indicate clustering of the stages, showing that the “middle” stage predicted

probabilities across a majority of the eggshells are more similar to the “late” stage probabilities than to those of the “early” stage.

Laser scan + optical image overlay



Fig. S 15: Cross sectional profiles of laser microscopy scans showing cassowary (*Casuarius* spp.) eggshell interior surface topography (Sample ID 1249).



## OnePredictorStage

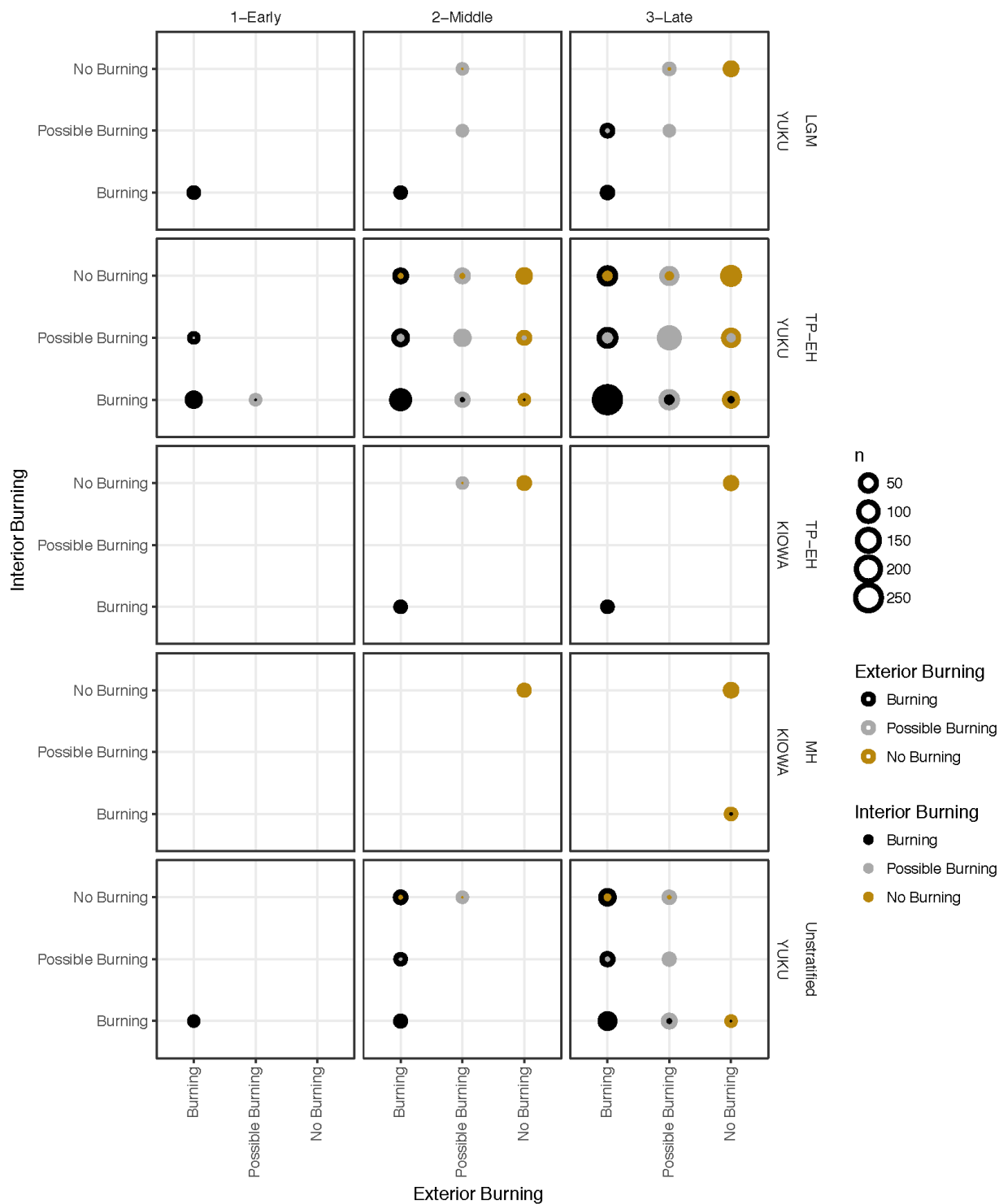


Fig. S 17: Density plot showing eggshell interior and exterior burning according to eggshell ontogenetic stage (1 = “Early”, 2 = “Middle”, and 3 = “Late”) prediction using the one-predictor model, and according to chronological phase at Kiowa and Yuku.



**Table S 1:** AMS 14C measurements from avian eggshell remains from Kiowa and Yuku. Dates were calibrated with OxCal 4.4. using IntCal2020 (87).

| Site | Level      | PSU AMS # | Sample ID | Taxon                 | Material  | Fraction Modern | ±      | D <sup>14</sup> C (‰) | ±2  | <sup>14</sup> C age (BP) | ±3  | Calibrated date (2s Intcal 2020)  |
|------|------------|-----------|-----------|-----------------------|-----------|-----------------|--------|-----------------------|-----|--------------------------|-----|---|
| Yuku | 6          | PSU-4303  | Y26A1     | <i>Casuarius</i> spp. | Carbonate | 0.1680          | 0.0019 | -832.0                | 1.9 | 14330                    | 100 | 17,822–17,115 cal BP (95.4%)  |
| Yuku | 6          | PSU-8893  | 1149      | <i>Casuarius</i> spp. | Carbonate | 0.1680          | 0.0009 | -832.0                | 0.9 | 14330                    | 45  | 17,780–17,289 cal BP (95.4%)  |
| Yuku | 6          | PSU-4302  | Y16A7     | <i>Casuarius</i> spp. | Carbonate | 0.1764          | 0.0019 | -823.6                | 1.9 | 13940                    | 90  | 17,286–17,185 cal BP (3.7%);<br>17,139–16,605 (91.7%)   |
| Yuku | 5C         | PSU-4301  | Y15C3     | <i>Casuarius</i> spp. | Carbonate | 0.2264          | 0.0019 | -773.6                | 1.9 | 11930                    | 70  | 14,022–13,907 cal BP (26.2%);<br>13,890–13,605 cal BP (69.3%)                                 |
| Yuku | 4C         | PSU-8907  | 2058      | <i>Casuarius</i> spp. | Carbonate | 0.2945          | 0.0010 | -705.5                | 1.0 | 9820                     | 30  | 11,264–11,195 cal BP (95.4%)  |
| Yuku | 4A         | PSU-8906  | 1816      | <i>Casuarius</i> spp. | Carbonate | 0.3022          | 0.0009 | -697.8                | 0.9 | 9610                     | 25  | 11,165–11,061 cal BP (23.8%);<br>11,039–10,998 cal BP (9.6%);<br>10,972–10,781 cal BP (62.0%) |
| Yuku | 4A         | PSU-8905  | 1804      | <i>Casuarius</i> spp. | Carbonate | 0.3027          | 0.0009 | -697.3                | 0.9 | 9600                     | 25  | 11,146–10,995 cal BP (31.0%);<br>10,975–10,773 cal BP (64.4%)                                 |
| Yuku | CR1<br>1+2 | PSU-8900  | 1401      | <i>Casuarius</i> spp. | Carbonate | 0.3140          | 0.0009 | -686.0                | 0.9 | 9305                     | 25  | 10,581–10,478 cal BP (70.3%);<br>10,472–10,410 cal BP (25.1%)                                 |
| Yuku | 3A         | PSU-8901  | 1430      | <i>Casuarius</i> spp. | Carbonate | 0.3154          | 0.0010 | -684.6                | 1.0 | 9270                     | 25  | 10,567–10,367 cal BP (88.8%);<br>10,358–10,339 cal BP (3.2%);<br>10,320–10,302 cal BP (3.4%)  |
| Yuku | 3A         | PSU-8902  | 1453      | <i>Casuarius</i> spp. | Carbonate | 0.3168          | 0.0010 | -683.2                | 1.0 | 9235                     | 30  | 10,505–10,263 cal BP (95.4%)  |
| Yuku | CR2        | PSU-8896  | 1347      | <i>Casuarius</i> spp. | Carbonate | 0.3182          | 0.0009 | -681.8                | 0.9 | 9200                     | 25  | 10,488–10,463 cal BP (8.7%);<br>10,431–10,250 cal BP (86.8%)                                  |
| Yuku | CR2        | PSU-8895  | 1337      | <i>Casuarius</i> spp. | Carbonate | 0.3200          | 0.0010 | -680.0                | 1.0 | 9155                     | 25  | 10,406–10,237 cal BP (95.4%)  |

| Site  | Level   | PSU AMS # | Sample ID | Taxon                 | Material  | Fraction Modern | ±      | D <sup>14</sup> C (‰) | ±2  | <sup>14</sup> C age (BP) | ±3 | Calibrated date (2s Intcal 2020)  |
|-------|---------|-----------|-----------|-----------------------|-----------|-----------------|--------|-----------------------|-----|--------------------------|----|---|
| Yuku  | CR1 1+2 | PSU-8898  | 1369      | <i>Casuarius</i> spp. | Carbonate | 0.3224          | 0.0010 | -677.6                | 1.0 | 9095                     | 25 | 10,288–10,200 cal BP (95.4%)  |
| Yuku  | 2       | PSU-4365  | Y12-1     | <i>Casuarius</i> spp. | Carbonate | 0.3333          | 0.0018 | -666.7                | 1.8 | 8825                     | 45 | 10,152–10,056 cal BP (18.9%);<br>10,048–9,982 cal BP (10.0%);<br>9,968–9,690 cal BP (66.6%)   |
| Yuku  | CR1 1+2 | PSU-8899  | 1388      | <i>Casuarius</i> spp. | Carbonate | 0.3382          | 0.0009 | -661.8                | 0.9 | 8710                     | 25 | 9,749–9,548 cal BP (95.4%)  |
| Yuku  | 3A      | PSU-4366  | Y1A3A-4   | <i>Casuarius</i> spp. | Carbonate | 0.3384          | 0.0018 | -661.6                | 1.8 | 8705                     | 45 | 9,889–9,844 cal BP (5.4%); 9,807–9,805 cal BP (0.2%); 9,789–9,543 cal BP (89.9%)  |
| Yuku  | CR2     | PSU-8894  | 1336      | <i>Casuarius</i> spp. | Carbonate | 0.3443          | 0.0010 | -655.7                | 1.0 | 8565                     | 25 | 9,550–9,521 cal BP (78.9%); 9,515–9,488 cal BP (16.6%)  |
| Yuku  | 2       | PSU-8897  | 1361      | <i>Casuarius</i> spp. | Carbonate | 0.3463          | 0.0011 | -653.7                | 1.1 | 8520                     | 25 | 9,540–9,482 cal BP (95.4%)  |
| Kiowa | 12      | PSU-4367  | KEE12-1   | Aves spp.             | Carbonate | 0.2737          | 0.0019 | -726.3                | 1.9 | 10410                    | 60 | 12,604–12,540 cal BP (7.7%);<br>12,493–12,001 cal BP (87.7%)  |
| Kiowa | 11      | PSU-8903  | 1486      | <i>Casuarius</i> spp. | Carbonate | 0.2833          | 0.0010 | -716.7                | 1.0 | 10130                    | 30 | 11,928–11,912 cal BP (1.1%);<br>11,882–11,611 cal BP (92.2%);<br>11,525–11,506 cal BP (1.8%);<br>11,418–11,413 cal BP (0.3%)                                      |
| Kiowa | 8       | PSU-4371  | KEE8-2    | <i>Casuarius</i> spp. | Carbonate | 0.3649          | 0.0018 | -635.1                | 1.8 | 8100                     | 40 | 9,261–9,233 cal BP (1.5%); 9,199–9,180 cal BP (1.4%); 9,136–8,980 cal BP (87.3%); 8,914–8,897 cal BP (1.2%); 8,880–8,865 cal BP (1.0%); 8,829–8,786 cal BP (3.0%) |
| Kiowa | 4       | PSU-4368  | KEE4-1    | Aves spp.             | Carbonate | 0.4625          | 0.0018 | -537.5                | 1.8 | 6195                     | 35 | 7,244–7,211 cal BP (5.3%); 7,169–6,984 cal BP (90.2%)   |

| Site  | Level | PSU AMS # | Sample ID | Taxon                 | Material  | Fraction Modern | ±      | D <sup>14</sup> C (‰) | ±2  | <sup>14</sup> C age (BP) | ±3 | Calibrated date (2s Intcal 2020)   |
|-------|-------|-----------|-----------|-----------------------|-----------|-----------------|--------|-----------------------|-----|--------------------------|----|--|
| Kiowa | 2A    | PSU-8904  | 1494      | <i>Casuarius</i> spp. | Carbonate | 0.4699          | 0.0010 | -530.1                | 1.0 | 6065                     | 20 | 6,987–6,852 cal BP (93.8%); 6,812–6,804 cal BP (1.7%)                            |
| Kiowa | 6     | PSU-4369  | KEE6-1    | <i>Casuarius</i> spp. | Carbonate | 0.4719          | 0.0018 | -528.1                | 1.8 | 6035                     | 30 | 6,975–6,966 cal BP (0.9%); 6,960–6,788 cal BP (94.6%)                            |
| Kiowa | 3     | PSU-4370  | KEE3-1    | <i>Casuarius</i> spp. | Carbonate | 0.4820          | 0.0017 | -518.0                | 1.7 | 5860                     | 30 | 6,777–6,768 cal BP (1.0%); 6,748–6,606 cal BP (91.4%); 6,584–6,565 cal BP (3.1%) |

Table S 2: NISP and proportions of eggshell by site, chronological phase and excavation unit

| Phase and Excavation Unit                      | KIOWA     |                 | YUKU       |                 | Overall Assemblage |                       |
|--|-----------|-----------------|------------|-----------------|--------------------|-----------------------|
|  | NISP      | % of assemblage | NISP       | % of assemblage | Total NISP         | Total % of assemblage |
| <b>Last Glacial Maximum</b>                    |           | <b>0.00%</b>    | <b>28</b>  | <b>2.75%</b>    | <b>28</b>          | <b>2.75%</b>          |
| 1  |           | 0.00%           | 8          | 0.79%           | 8                  | 0.79%                 |
| 2  |           | 0.00%           | 1          | 0.10%           | 1                  | 0.10%                 |
| CR2  |           | 0.00%           | 19         | 1.86%           | 19                 | 1.86%                 |
| <b>Terminal Pleistocene and Early Holocene</b> | <b>17</b> | <b>1.67%</b>    | <b>867</b> | <b>85.08%</b>   | <b>884</b>         | <b>86.75%</b>         |
| 1  |           | 0.00%           | 27         | 2.65%           | 27                 | 2.65%                 |
| 2  |           | 0.00%           | 24         | 2.36%           | 24                 | 2.36%                 |
| 1-2  |           | 0.00%           | 5          | 0.49%           | 5                  | 0.49%                 |
| 1A   |           | 0.00%           | 418        | 41.02%          | 418                | 41.02%                |
| 2+1-2  |           | 0.00%           | 12         | 1.18%           | 12                 | 1.18%                 |
| CR1  |           | 0.00%           | 176        | 17.27%          | 176                | 17.27%                |

|                     |           |              |            |               |             |                |
|---------------------|-----------|--------------|------------|---------------|-------------|----------------|
| EE                  | 17        | 1.67%        |            | 0.00%         | 17          | 1.67%          |
| SB                  |           | 0.00%        | 169        | 16.58%        | 169         | 16.58%         |
| TR                  |           | 0.00%        | 36         | 3.53%         | 36          | 3.53%          |
| <b>Mid-Holocene</b> | <b>14</b> | <b>1.37%</b> |            | <b>0.00%</b>  | <b>14</b>   | <b>1.37%</b>   |
| EE                  | 9         | 0.88%        |            | 0.00%         | 9           | 0.88%          |
| SE                  | 5         | 0.49%        |            | 0.00%         | 5           | 0.49%          |
| <b>Unstratified</b> |           | <b>0.00%</b> | <b>93</b>  | <b>9.13%</b>  | <b>93</b>   | <b>9.13%</b>   |
| <b>Grand Total</b>  | <b>31</b> | <b>3.04%</b> | <b>988</b> | <b>96.96%</b> | <b>1019</b> | <b>100.00%</b> |

Table S 3: Recorded evidence of human-cassowary from the Late Pleistocene-Holocene in New Guinea

| Province | Site Name | Site code | Type | masl | Distance from coast | Max age cal BP | Min age cal BP | Site Type                             | Cassowary eggshell  | Cassowary bone        | Cassowary artifacts   | References |
|----------|-----------|-----------|------|------|---------------------|----------------|----------------|---------------------------------------|---|-----------------------|---|------------|
| Chimbu   | Kiowa     | NAW       | RS   | 1500 | 95 km               | 11,630-12,589  | 0-303          | Foraging camp (small game)            | 12ka–1ka (or later)   | 12ka–1ka (or later)   | 9ka–1ka (or later, possibly 10ka if worked bone from 10A is cassowary, not previously reported) | 1, 2, 3    |
| Chimbu   | Nombe     | NCA       | Cave | 1750 | 95 km               | 34,826-38,781  | 33-253         | Foraging camp (small game; megafauna) | 20ka–0.2ka (or later) absent from Stratum D (MIS-3) and only one fragment from Stratum C (LGM), most from 13ka to late Holocene | 36ka–0.2ka (or later) | Unknown (bone artefacts present through deposit but not identified)                             | 4, 5       |

| Province                 | Site Name        | Site code  | Type      | masl        | Distance from coast | Max age cal BP       | Min age cal BP     | Site Type                                      | Cassowary eggshell   | Cassowary bone  | Cassowary artifacts  | References |
|--------------------------|------------------|------------|-----------|-------------|---------------------|----------------------|--------------------|--|--|---|--|------------|
| Western Highlands        | Yuku             | MAH        | RS        | 1280        | 180 km              | 17,063-17,828        | 32-254             | Foraging camp (small game); burial; ceremonial | 17ka–9ka (possibly later depending on the stratigraphic association of eggshells from Level 2 and 3)                               | None  | None (spatula not ID to species present in Level 5A plus other occasional bone points throughout the sequence) | 6, 7, 3    |
| Western Highlands        | Kamapuk          | -          | RS        | 2050        | 170 km              | 4,628-5,296          | 2,364-2,759        | Foraging camp (small game)                     | -  | ~5ka (but not later)  | -  | 8          |
| <u>Eastern Highlands</u> | <u>Kafiavana</u> | <u>NBZ</u> | <u>RS</u> | <u>1350</u> | <u>90 km</u>        | <u>11,404-13,309</u> | <u>4,877-5,739</u> | <u>Foraging camp (small game)</u>              | <u>&gt;5ka (mostly concentrated in Horizon III below a date of 4690 BP)</u>  | <u>None</u>   | <u>Unknown (bone artefacts present through deposit but not identified)</u>                                     | <u>9</u>   |
| Eastern Highlands        | Aibura           | NAE        | Cave      | 1640        | 100 km              | 3,888-4,514          | 555-914            | Foraging camp (small game)                     | ~0.7ka or 3.8ka - difficult to assess given sparse dating and lack of correlation to stratigraphy,,but site dates to late Holocene | ~0.7ka or 3.8ka - a distal phalange probably cassowary from Square II Level 2 no dates for this context,but site dates to late Holocene | ~0.7ka or 3.8ka possible broken cassowary spatula plus other avian bone tools through the deposit              | 9          |

| Province          | Site Name    | Site code | Type | masl | Distance from coast | Max age cal BP | Min age cal BP | Site Type                  | Cassowary eggshell                                      | Cassowary bone                               | Cassowary artifacts   | References |
|-------------------|--------------|-----------|------|------|---------------------|----------------|----------------|----------------------------|---|--|---|------------|
| Eastern Highlands | Batari       | NBY       | Cave | 1300 | 115 km              | 18,642-21,740  | 698-916        | Foraging camp (small game) | 18ka–0.7ka (although dating done in the 60s)            | None   | Unknown (bone artefacts present through deposit but not identified) | 9          |
| Sepik             | Lachitu      | RIQ       | Cave | 25   | 0.15 km             | 28,092–29453   | 0-278          | Foraging camp (small game) | -   | Mid Holocene'                                | -   | 10         |
| Gulf              | Bageima      | -         | Open | 25   | 50 km               | -              | 20th century   | Settlement                 | 20th century  | None   | None  | 11         |
| Gulf              | Ouloubomot o | -         | Cave | 25   | 50 km               | 121-804        | -              | Foraging camp (small game) | >0.1ka-recent (pre-Ceramic dated to older than 1050 BP) | <0.1ka (Early Ceramic period around 1050 BP) | None  | 11         |
| Gulf              | Herekuna     | -         | RS   | 25   | 50 km               | -              | 20th century   | Foraging camp (small game) | 20th century (Ceramic and Recent Historic period)       | None   | None  | 11         |
| Central           | Motupore     | -         | Open | 0    | 0 km                |                |                | Settlement                 | None  | None   | ~0.5ka (last millennium BP)   | 12         |
| Central           | Nebira       | -         | Open |      |                     |                |                | Settlement                 | None  | Present within last millennium BP            |   | 13         |
| Central           | Oposisi      | ADI       | Open |      | 0 km                |                |                | Settlement                 | None  | Present between 2ka-0ka (need to check)      |   | 14         |

| Province   | Site Name          | Site code | Type | masl | Distance from coast | Max age cal BP | Min age cal BP | Site Type                  | Cassowary eggshell   | Cassowary bone                           | Cassowary artifacts | References |
|------------|--------------------|-----------|------|------|---------------------|----------------|----------------|----------------------------|--|--|---------------------|------------|
|            |                    |           |      |      |                     |                |                |                            |  | exactly when)                            |                     |            |
| Central    | Urourina           | ADG       | Open |      |                     |                |                | Settlement                 | None   | Present within last millennium BP        |                     | 14         |
| West Papua | Toé                | -         | Cave |      |                     |                |                | Foraging camp (small game) | 30ka-10ka peak in lower levels   | 30ka-late Holocene, peak in lower levels | Possible            | 15         |
| West Papua | Kria               | -         | Cave |      |                     |                |                | Foraging camp (small game) | 7-6ka directly dated (but eggshells present into upper undated layers) | 7-6ka                                    | Possible            | 15         |
| Maluku     | Liang Lemdubu      | -         | Cave |      |                     |                |                | Foraging camp (small game) | 20ka-<1.5ka (or later)   | 20ka-1ka                                 | None                | 16         |
| Maluku     | Liang Nabulei Lisa | -         | Cave |      |                     |                |                | Foraging camp (small game) | 16ka-recent  | None                                     | None                | 16         |

**Notes:** Cassowary remains do not appear to have been commonly collected at any site in the Eastern Highlands, but were in Chintheap (1980 due to lower forest cover in the east). Cassowary cranial elements are rare at Nombe and absent at Kiowa. It is possible that cassowary were overhunted at Kamapuk after the mid-Holocene (11-21) as they system was close to Kuk Swamp and major forest clearances and landscape modification took place earlier in Denham and Nombe than at Kiowa where there was longer forest persistence. Cassowary bone rare in Pleistocene Nombe deposits (only one bone present in deepest deposit [Stratum D26/B] perhaps due to expanding grasslands in MIS-3 and 2, but evidence of population increased at start of the Holocene.

#### References:

1: Bulmer 1964  
2: Denham 2016

7: Denham 2016b

8: Christiansen 1975

9: White 1972

10: O'Connor et al. 2011

15: Pasveer 2004

16: O'Connor et al. 2005a

Table S 4: Matrix of chronological phase to weathering by eggshell NISP

| Phase                               | Weathering* |     |     |    | Total |
|-------------------------------------|-------------|-----|-----|----|-------|
|                                     | 1           | 2   | 3   | 4  |       |
| Last Glacial Maximum                | 2           | 15  | 7   | 4  | 28    |
| Terminal Pleistocene/Early Holocene | 162         | 409 | 267 | 46 | 884   |
| Mid-Holocene                        | 4           | 1   | 9   | 0  | 14    |
| Unstratified                        | 13          | 12  | 65  | 3  | 93    |
| <b>Total</b>                        | 181         | 437 | 348 | 53 | 1019  |

\*1: Light; features clearly defined; 2: Medium-Light; features clearly defined in some areas; 3: Medium-Extreme; features distinguishable but extremely weathered; 4: Extreme; features not visible

Table S 5: NISP of cassowary eggshell predicted to have been harvested at “Early”, “Middle”, and “Late” stages of ontogeny using the 1-predictor and 4-predictor models, across chronological phases

|  | 1-predictor model |                   | 4-predictor model |                   |
|--|-------------------|-------------------|-------------------|-------------------|
|  | KIOWA             | YUKU              | KIOWA             | YUKU              |
| <b>Last Glacial Maximum</b>                | <b>No samples</b> | <b>28</b>         | <b>No samples</b> | <b>28</b>         |
| Early Stage                                | -                 | 2                 | -                 | 2                 |
| Middle Stage                               | -                 | 4                 | -                 | 22                |
| Late Stage                                 | -                 | 22                | -                 | 4                 |
| <b>Terminal Pleistocene/Early Holocene</b> | <b>17</b>         | <b>867</b>        | <b>17</b>         | <b>867</b>        |
| Early Stage                                | 0                 | 22                | 0                 | 28                |
| Middle Stage                               | 8                 | 168               | 15                | 644               |
| Late Stage                                 | 9                 | 677               | 2                 | 195               |
| <b>Mid-Holocene</b>                        | <b>14</b>         | <b>No samples</b> | <b>14</b>         | <b>No samples</b> |
| Early Stage                                | 0                 | -                 | 0                 | -                 |
| Middle Stage                               | 3                 | -                 | 7                 | -                 |
| Late Stage                                 | 11                | -                 | 7                 | -                 |
| <b>Unstratified</b>                        | <b>No samples</b> | <b>93</b>         | <b>No samples</b> | <b>93</b>         |
| Early Stage                                | -                 | 1                 | -                 | 1                 |
| Middle Stage                               | -                 | 11                | -                 | 52                |
| Late Stage                                 | -                 | 81                | -                 | 40                |
| <b>Grand Total</b>                         | <b>31</b>         | <b>988</b>        | <b>31</b>         | <b>988</b>        |

Table S 6: Comparison of agreement between 1-predictor and 4-predictor model eggshell developmental stage predictions

| One Predictor Model | Four Predictor Model |            |          |
|---------------------|----------------------|------------|----------|
|                     | 1 (Early)            | 2 (Middle) | 3 (Late) |



|                   |           |            |            |
|-------------------|-----------|------------|------------|
| <b>1 (Early)</b>  | <b>13</b> | <b>1</b>   | <b>0</b>   |
| <b>2 (Middle)</b> | <b>6</b>  | <b>165</b> | <b>8</b>   |
| <b>3 (Late)</b>   | <b>0</b>  | <b>545</b> | <b>231</b> |

Table S 7: NISP of cassowary eggshell identified through visual assessment of cone microstructure erosion (CME) as having been harvested during the “pre-pitting” (equivalent to the “Early” stage in the predictive models) versus “pitting” stage (equivalent to the later part of the “Middle” stage and to the “Late” stage in the predictive models), across chronological phases.

|  | CME       |            |             |
|--|-----------|------------|-------------|
|  | KIOWA     | YUKU       | Grand Total |
| <b>Last Glacial Maximum</b>                            |           | <b>28</b>  | <b>28</b>   |
| 1: Pre-pitting stage                                   |           | 1          | 1           |
| 2: Pitting visible                                     |           | 12         | 12          |
| 3: Pitting visible; diagnostic features weathered      |           | 11         | 11          |
| 4: Features too weathered to distinguish erosion stage |           | 4          | 4           |
| <b>Terminal Pleistocene and Early Holocene</b>         | <b>17</b> | <b>867</b> | <b>884</b>  |
| 1: Pre-pitting stage                                   | 8         | 158        | 166         |
| 2: Pitting visible                                     | 3         | 359        | 362         |
| 3: Pitting visible; diagnostic features weathered      | 3         | 183        | 186         |
| 4: Features too weathered to distinguish erosion stage | 3         | 167        | 170         |
| <b>Mid-Holocene</b>                                    | <b>14</b> |            | <b>14</b>   |
| 1: Pre-pitting stage                                   | 3         |            | 3           |
| 2: Pitting visible                                     | 2         |            | 2           |
| 3: Pitting visible; diagnostic features weathered      | 3         |            | 3           |
| 4: Features too weathered to distinguish erosion stage | 6         |            | 6           |
| <b>Unstratified</b>                                    |           | <b>93</b>  | <b>93</b>   |
| 1: Pre-pitting stage                                   |           | 19         | 19          |
| 2: Pitting visible                                     |           | 8          | 8           |
| 3: Pitting visible; diagnostic features weathered      |           | 19         | 19          |
| 4: Features too weathered to distinguish erosion stage |           | 47         | 47          |
| <b>Grand Total</b>                                     | <b>31</b> | <b>988</b> | <b>1019</b> |

Table S 8: Comparison of prediction from 1-predictor model and visual inspection of cone microstructure erosion (CME)

| One Predictor Model | CME*       |            |            |            | Total      |
|---------------------|------------|------------|------------|------------|------------|
|                     | 1          | 2          | 3          | 4          |            |
| <b>1 (Early)</b>    | 1          | 1          | 6          | 6          | <b>14</b>  |
| <b>2 (Middle)</b>   | 65         | 57         | 48         | 9          | <b>179</b> |
| <b>3 (Late)</b>     | 125        | 327        | 164        | 160        | <b>776</b> |
| <b>Total</b>        | <b>191</b> | <b>385</b> | <b>218</b> | <b>175</b> | <b>969</b> |

\*1: Pre-pitting stage; 2: Pitting visible; 3: Pitting visible; diagnostic features weathered; 4: Features too weathered to distinguish erosion stage

Table S 9: Comparison of prediction from 4-predictor model and visual inspection of cone microstructure erosion (CME)

| Four Predictor Model | CME*       |            |            |            | Total      |
|----------------------|------------|------------|------------|------------|------------|
|                      | 1          | 2          | 3          | 4          |            |
| <b>1 (Early)</b>     | 1          | 2          | 10         | 6          | <b>19</b>  |
| <b>2 (Middle)</b>    | 154        | 328        | 159        | 70         | <b>711</b> |
| <b>3 (Late)</b>      | 36         | 55         | 49         | 99         | <b>239</b> |
| <b>Total</b>         | <b>191</b> | <b>385</b> | <b>218</b> | <b>175</b> | <b>969</b> |

\*1: Pre-pitting stage; 2: Pitting visible; 3: Pitting visible; diagnostic features weathered; 4: Features too weathered to distinguish erosion stage

Table S 10: Total eggshell NISP according to chronological phase and percentages of each phase's total NISP with indications of burning on the eggshell exterior and interior surfaces.

|  | Eggshell Exterior |            | Eggshell Interior |            |
|--|-------------------|------------|-------------------|------------|
|  | KIOWA             | YUKU       | KIOWA             | YUKU       |
| <b>Last Glacial Maximum</b>                |                   | <b>28</b>  |                   | <b>28</b>  |
| Burning                                    |                   | 46%        |                   | 29%        |
| No Burning                                 |                   | 36%        |                   | 46%        |
| Possible Burning                           |                   | 18%        |                   | 25%        |
| <b>Terminal Pleistocene/Early Holocene</b> | <b>17</b>         | <b>867</b> | <b>17</b>         | <b>867</b> |
| Burning                                    | 24%               | 57%        | 24%               | 49%        |
| No Burning                                 | 71%               | 16%        | 76%               | 21%        |
| Possible Burning                           | 6%                | 27%        | 0%                | 30%        |
| <b>Mid-Holocene</b>                        | <b>4</b>          |            | <b>4</b>          |            |
| No Burning                                 | 100%              |            | 100%              |            |
| <b>Late Holocene</b>                       | <b>10</b>         |            | <b>10</b>         |            |
| Burning                                    |                   |            | 20%               |            |
| No Burning                                 | 100%              |            | 80%               |            |
| <b>Unstratified</b>                        |                   | <b>93</b>  |                   | <b>93</b>  |
| Burning                                    |                   | 80%        |                   | 53%        |
| No Burning                                 |                   | 1%         |                   | 34%        |
| Possible Burning                           |                   | 19%        |                   | 13%        |
| <b>Total</b>                               | <b>31</b>         | <b>988</b> | <b>31</b>         | <b>988</b> |

Table S 11: Association between exterior color and morphological assessment of eggshell developmental stage (CME). Expected values if the variables are independent are indicated within brackets: green indicates higher expected counts than observed and blue indicates lower expected counts than observed.

| Exterior Burn | CME* | Total |
|---------------|------|-------|
|---------------|------|-------|

|                         | 1         | 2         | 3         | 4        |     |
|-------------------------|-----------|-----------|-----------|----------|-----|
| <b>Burning</b>          | 128 (106) | 181 (215) | 123 (122) | 110 (98) | 542 |
| <b>Possible Burning</b> | 35 (50)   | 119 (102) | 57 (58)   | 46 (47)  | 257 |
| <b>No Burning</b>       | 26 (33)   | 84 (66)   | 38 (38)   | 19 (30)  | 167 |
| <b>Total</b>            | 189       | 384       | 218       | 175      |     |

\*1: Pre-pitting stage; 2: Pitting visible; 3: Pitting visible; diagnostic features weathered; 4: Features too weathered to distinguish erosion stage

\*\* *p*-value for the chi-square test of independence=5.698e-05

Table S 12: Association between interior color and morphological assessment of eggshell developmental stage (CME). Expected values if the variables are independent are indicated within parentheses: (green) indicates higher expected counts than observed and (blue) indicates lower expected counts than observed.

| <b>Interior Burn</b>    | <b>CME*</b> |           |          |         | <b>Total</b> |
|-------------------------|-------------|-----------|----------|---------|--------------|
|                         | 1           | 2         | 3        | 4       |              |
| <b>Burning</b>          | 83 (87)     | 157 (176) | 111(100) | 93 (80) | 444          |
| <b>Possible Burning</b> | 54 (54)     | 135 (109) | 55 (62)  | 31(50)  | 275          |
| <b>No Burning</b>       | 52 (48)     | 92 (98)   | 52 (56)  | 51 (45) | 247          |
| <b>Total</b>            | 189         | 384       | 218      | 175     |              |

\*1: Pre-pitting stage; 2: Pitting visible; 3: Pitting visible; diagnostic features weathered; 4: Features too weathered to distinguish erosion stage

\*\* *p*-value for the chi-square test of independence=0.001693