MODELING PAST AND PRESENT IN THE EASTERN HIGHLANDS OF PAPUA NEW GUINEA

J. David Cole

Research Affiliate, The Burke Museum of Natural History and Culture,
University of Washington
Email: jdcole4@frontier.com

K.J. Pataki-Schweizer

Research Affiliate, The Burke Museum of Natural History and Culture,
University of Washington
Email: kjpataki@gmail.com

Keywords: PNG, Papua New Guinea, highlands, model, GIS, prehistory, archaeology, dispersal, subsistence

ABSTRACT

The existence of "fringe societies" in Papua New Guinea has long been recognized by anthropologists. In the New Guinea Highlands, the term refers to peoples who occupy the fringes of more populous and better-known valleys. In many instances, these groups also subsist on staples other than Ipomoea batatas, *more commonly known as sweet potato, a tuber introduced to the highlands within the last 300 years. The Awa at the far eastern edge of the Eastern Highlands are such a group, and the word fringe has often been used to describe them. Surprisingly, anthropologists and archaeologists have not seized on the possibility that their unusual subsistence represents a survival of a previous adaptation that has not completed its conversion to the new crop. The authors of this paper use the Awa economy to model a pre-ipomoean past for members of the Tairora language subfamily, namely, the South Tairora, Auyana, and Awa languages. Using archaeological, paleoenvironmental, demographic, and ethnohistorical data from our study area; data for Awa from ethnographer David Boyd's research; and other sources and simulation modeling, we explore long-standing questions about the dispersal of early horticultural peoples, its determinants, the differentiation of languages, possible time frames for their migrations, and impacts on the resulting landscapes.*

INTRODUCTION

This paper concerns the prehistory of an area in the island of New Guinea and its relation to the present. We focus on a population in the Eastern Highlands concentrated between 1200 and 2200 meters above sea-level (Figure 1) and the landscape they have occupied for over 21,000 years, with special attention to horticultural developments in the late Holocene. This landscape has extensive areas of long and short grasses and secondary growth, surrounded by primary forests that reappeared in the late Pleistocene and early Holocene as forest lines rose with warming temperatures.

Our project focuses on landscapes occupied by speakers of the Kainantu Language Subfamily (Figure 2) composed of the Agarabi, Auyana, Awa, Gadsup, and Tairora language communities and their dialects. Prior to the historic period, its speakers were organized as small-scale societies with political institutions based largely on kinship and authority achieved within each generation. Their subsistence was horticultural combined with hunting and foraging, with considerable reliance on grassland and forest fallowing, forest clearance, and bamboo irrigation systems in South Tairora, Awa, and the southeastern edge of South Fore.

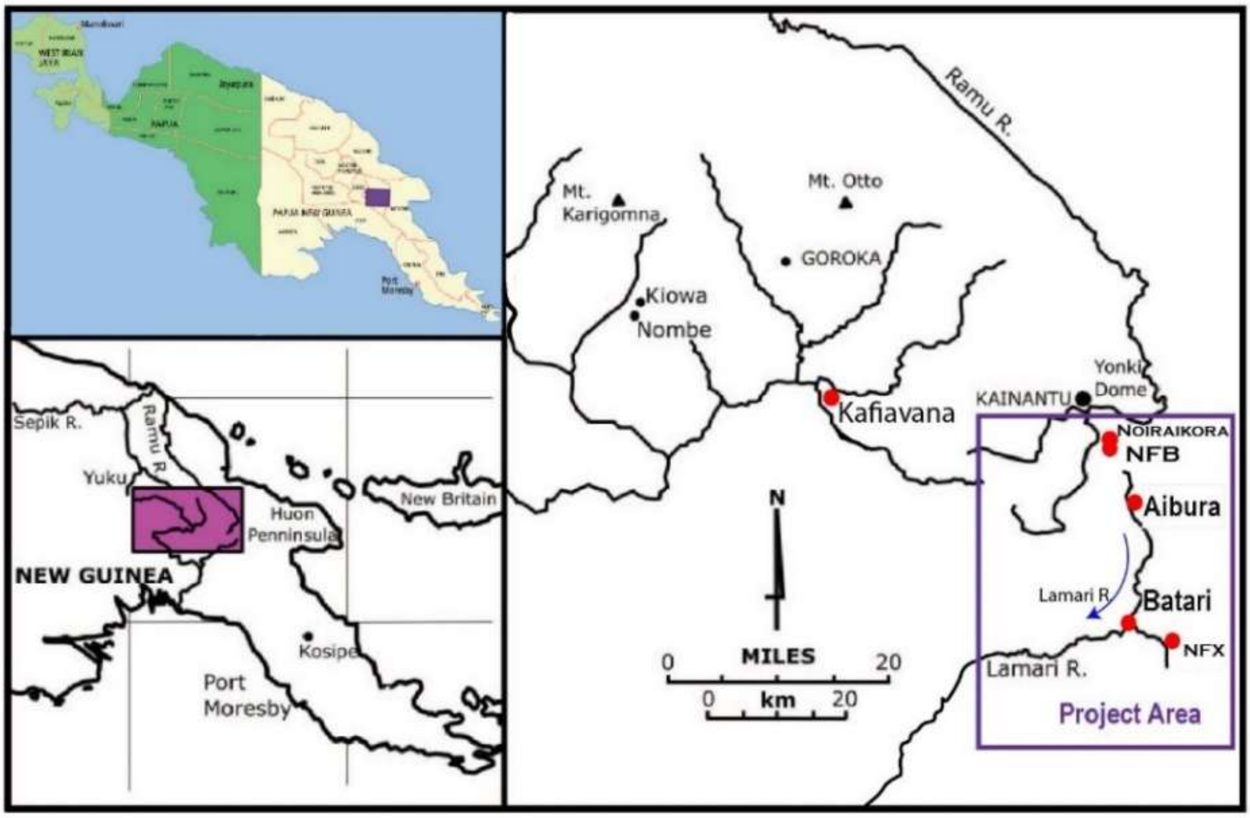

Figure 1. Map of project area: Source: (Cole 1996, Figure 1:12).

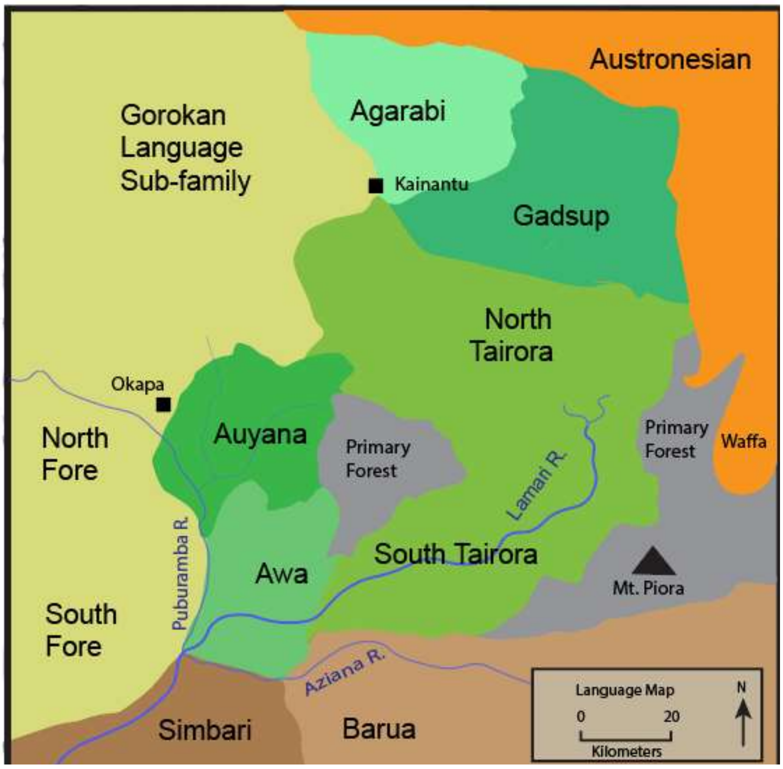

Figure 2. Green shades are members of the Kainantu Language Sub-family, yellow is Gorokan, orange is non-highland Austronesian language, brown shades are Angan. The people of New Guinea speak more than 800 languages, including the non-Austronesian Trans–New Guinea Language Phylum and its Kainantu-Goroka Family. Source: The Authors, based on Pawley (2005:67–107).

The historic period in Gadsup began in 1919 with the first visits of missionaries, followed by miners and administrative personnel who spread through the major northern valleys until the interruption of World War II. The war led to an increase of Western influence by Allied forces, and Australian pacification in the major northern basins was well established by the war's end in 1945. Long after the central basins occupied by Agarabi, Gadsup, and North Tairora speakers were pacified and de-restricted, populations in our project area, in the South Tairora and Awa language areas, engaged in frequent clan warfare and on occasion threatened early administration patrols after the war. The first postwar patrol into Awa and South Tairora was in 1947, and neither region was considered pacified and unrestricted until 1963 (Skinner, Kainantu Patrol Reports, Vol 1, 1943–1949, No. 5, 47–48). Auyana speakers were more accessible and adapted more easily to administrative advances, including their own cargo-cult responses (Pataki-Schweizer 1980:78–79); they were considered pacified prior to 1953 when the Okapa station was built and road and track construction into Fore and Auyana was underway (Robbins 1982:14). The impact of missionary activity was also notable (Pataki 1966). Change since WWII and especially after the 1960s has been rapid; see Supplement 1: Contact History in this issue.

ARCHAEOLOGICAL SUMMARY

Our study area includes the Kainantu basin, the Lamari River watershed, and the Auyana basin and its uplands. Judging from a charred and sharpened stake excavated at NFX (Figure 1), an open site in South Tairora, the earliest known human occupation in the study area dates to 20,067–23,713 calBP (Cole 1996; Watson and Cole 1977). This date is verified by an associated scatter sample of 20,471–20,701 calBP (Huff 2016a). These dates place occupation of the Lamari watershed during the Last Glacial Maximum in climate stage MIS 2. At that time, a cooler climate prevailed, the forest line had dropped below major highland basin floors, and the project area was covered by mixed grasses (Haberle 2007:219–228). As the climate warmed, mixed grasses were replaced with forests. Similarity of lithic tool types at NFX and Kafiavana (about 50 kilometers northwest of the Lamari Valley) with Late Pleistocene dates suggests a cultural affinity across the intervening region during the Late Pleistocene into the middle Holocene (Haberle 1996:1–11; Cole 1996; Huff 2016a; see Supplement 2).

The existence of tools capable of wood extraction (chopping) at Kafiavana prior to 9500 years ago suggests early occupation of basins north and west of the project area by foragers with base camps where extractive (chopping) tools were used and curated (White 1972). Deposits at Aibura and Batari dated between 8000 and 4000 years ago indicate forays into the Lamari Valley from the north during the middle Holocene. These visits left deposits of faunal remains, forest species that diminished over time, and highly reduced flake and core tools. There was no evidence of flaked stone choppers or polished stone adzes prior to 3000 BP. A functional analysis by Cole (1996) interprets these early deposits as evidence of temporary occupations by hunters and perhaps foragers who used these sites as limited-purpose camps. At this time, the project area was covered by primary intermontane forest, with no evidence of permanent occupation. The earliest signs of settled occupation and horticulture are found in the late Holocene in paleoecological cores from Noraikora swamp and at the NFB archaeological site, starting between 5000 and 4000 BP. The swamp cores contain signs of clearing and burning, and NFB includes stone bowl fragments and pottery in a stratified open site on an interfluve above the swamp, dating between ~3900 and ~3200 BP. Stone adzes appear towards the end of this period, and their increasing frequency at Aibura and Batari between ~3000 and ~2000 BP suggests that a population exercising a horticultural way of life was dispersing south into unoccupied forests of the Lamari watershed. This evidence led us to hypothesize that a pre-ipomoean horticultural people had already settled north of the Lamari watershed sometime after 4200 BP and migrated southward into the Lamari basin to populate the Lamari Valley and subsequently Awa and the

Auyana basin and uplands, in that order (Figure 3).

OVERVIEW: AGRICULTURE AND THE ENVIRONMENT

This report draws on the Agricultural Systems Project (ASP) as a framework for summarizing the agricultural features of the project area (Bourke *et al*. 2002). It focuses on the Lamari Valley, occupied by Tairora and Awa speakers and the Auyana basin and uplands where the Auyana language is spoken. The ASP provides information on agricultural practices and cropping patterns as part of an extensive geographical information system and database for Papua New Guinea. Its primary value for the present research lies in providing an outside and familiar context of reference for an experimental and relatively innovative approach to prehistory in Papua New Guinea. Its system of classification is based on fallow type, fallow period, cultivation intensity, staple type or types, garden and crop segregation, and methods of soil maintenance. Our concerns focus especially on the attributes of "staple crop" and "cultivation intensity" in our efforts to understand processes of migration and technological and subsistence change over the past 4200 years in the area and territory occupied by the Tairora Language Subfamily.

Within the ASP framework our study area falls into four classes: Nos. 1, 20, 5, and 6. Agricultural System 1 characterizes the northern basins occupied by speakers of North Tairora, Gadsup, and Agarabi (Figure 2). In this category sweet potato is the Dominant Staple and yam and winged bean (*Psophocarpus tetragonolobus*) are used for rotation. Taro is a less important crop. It is included as a staple, though it provides only 4% of the starch diet (see below). In Northern Tairora, Watson (1983:39) observed in the late 1950s and early 1960s that taro was grown opportunistically in small patches that provided significant moisture. Bourke *et al*. also report that since pacification, which was accomplished in Gadsup and Northern Tairora in the late 1930s and late 1940s, settlement and gardens shifted from ridgetops into the lower basins, where the soil contains higher levels of volcanic ash and is more fertile. Here the slopes are gentler and often require drainage rather than irrigation, especially for sweet potato, which has been grown commercially in North Tairora for the past three decades. In a survey conducted in 1982–1983, 217 families were asked over a ten-month period (with samples taken at two-month intervals) what they had consumed in the previous day. Summarizing, the results were 97% sweet potato, 6% banana, 4% taro, 2% cassava, 2% yam, 2% coconut, and 26% rice. In citing this report, Bourke *et al*. (2002:21) note that this diet represents the crop pattern in System 1 except for rice. Similar reporting by Du Toit, who studied Akuna in Gadsup for a year (1961–1962), affirms that taro was not grown in or near Akuna but was grown by, and presumably traded from, the people of the Arona valley on the north side of the Gadsup basin. It was not a major staple but was used occasionally. When used, it was often mixed with mashes or cooked in bamboo with sweet potato. It was more often consumed on ceremonial occasions. Taro gardens are not mentioned in Du Toit's land-use table, although 5% of cultivated land was listed as "miscellaneous"; a percentage for taro may have been included in that category (Du Toit 1974:172). System 1 extends into the bottleneck of the upper Lamari headwaters and includes Noraikora swamp and the Aibura archaeological site. It transitions to System 20 between Suwaira and Obura in a narrow zone that marks the transition between North and South Tairora (Bourke *et al*. 2002:21).

Agricultural System 20 extends from the headwaters of the Lamari River near Suwaira and Obura in the north to its confluence with the Puburamba and Aziana rivers in the southwest (Figure 4). The valley through which it flows is steep and deepens along its length. Its slopes and rugged benches are covered by short grasses, mainly *Imperata* and *Themeda* mixed with *Ischaemum, Arthraxon, Setaria*, and *Miscanthus*. *Themeda australis* is prominent on the steeper slopes where the topsoil is thinned by erosion; *Imperata cylindrica* prefers more gentle slopes where topsoil is deeper. These soils are tropical, rust-colored, and friable lithosols with a pH of 6.0 and less. There is a thin humus cover from a fraction of an inch (25.4 mm) to several inches with deeper and more numerous pockets downslope (Boyd 1975:70). Rainfall in this area ranges around 2000 mm per annum and is a possible source of considerable erosion on valley slopes which are often cultivated on grades of 30 degrees or more.

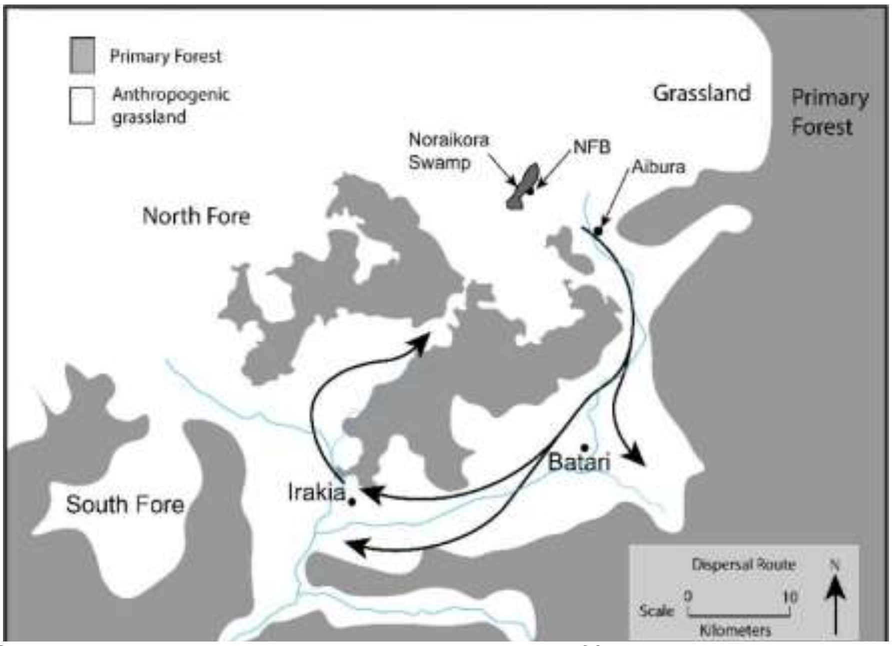

Figure 3. Dispersal of the Kainantu languages speakers, thought to be the result of fission and migration into the Lamari River drainage and the Auyana basin and uplands. Source:The authors.

Figure 4. Map of project area with Agricultural Systems (yellow text with white outline, Bourke et al.*2002), patrol stations (orange with dots), Tairora bounded complexes (orange, no dots), Awa (blue), Fore (red). Locations outside of Awa where bamboo irrigation systems have been observed or reported (blue cross-hatches). The Baira irrigation system was sighted in 1988 by Haberle and was used for coffee and possibly other crops then (Haberli pers.comm. 2020). Base map:Google Earth 2017 Maxar Technologies.*

The grasslands not immediately under cultivation are frequently burned. Manner (1969, 1976) conducted two investigations near Kompiai in the Jimi Valley (Western Highlands Provence) on the effects of shifting cultivation and fire on vegetation and soils. He concluded that shifting cultivation and burning affect some of the chemical and physical properties of the soils, increasing the base saturation, total bases, pH, decreasing organic matter and nitrogen. This degradation is intensified by repeated burnings which eventually reduce secondary regrowth to perpetual grassland. While his studies are based on limited soil analyses, they "provide strong evidence that tropical grasslands may be of anthropogenic origin" (Bleeker 1963:266–267).

A primary feature of Agricultural System 20 is the diversity of Dominant Staples. In Agricultural System 1, the Dominant Staple is sweet potato, with taro and yam as very minor supplements. This was the situation in the late 1950s and early 1960s when James Watson worked in North Tairora and Brian DuToit studied Gadsup, and it continues to be the case according to Bourke *et al*. (2002). In System 20, ethno-botanist Terence Hays, who studied in Ndumba in the middle Lamari Valley from 1971 to 1972, observed a different subsistence. While sweet potato was the Dominant Staple, large gardens were devoted to taro. These gardens were as large as 929 m^2, though most gardens were "slightly smaller" (Hays 1974:52). They were situated between 1600 m and 1700 m on the banks of the Malaria River, a southern tributary of the Lamari. Nevertheless, in 1971–72 the people of Ndumba and the surrounding populations of Anima, To'okena, Ahea, and Oraura were well on their way to adopting sweet potato as their Dominant Staple. Accordingly, they had cut back primary forest three to four kilometers to an altitude of 2200 m for sweet potato cultivation. While small taro patches were maintained above 1770m and closer to settlements, the bulk of their taro was grown in the larger gardens closer to the river. Hays's informants stated that "taro simply does not grow well at the higher levels" (Hays 1974:52).

In the middle Lamari Valley the proportion of taro and yam increases at the border zone between South Tairora and Awa. This increase was documented in detail by ethnographer David Boyd, who studied in Irakia Awa in 1971–1972. While the ASP names sweet potato as the "Dominant Staple" in System 20 in 1983, it recognizes a gradient in the importance of taro from the upper to the lower end of the Lamari Valley according to the following excerpt:

> Boyd's observations are consistent with early patrol reports on the lower Lamari and Aziana Valleys between the late 1940s and mid-1950s. These suggest an increase in the importance of taro relative to sweet potato further down the Lamari. For example, R. I. Skinner wrote: 'sweet potato seems to be the staple food (everywhere) [the 'everywhere' Skinner refers to is in Fore territory to the west of the Lamari and Puburamba rivers], except in Iraki (village) where no sweet potato gardens were seen—taro apparently being the most important part of the diet, although bananas were plentiful' (Kainantu Patrol Report Vol. 1, No. 5, 1947-48). In the lower villages of the Aziana Valley, G. Linsley noted that '...taro becomes almost the sole item of food with little yam or sweet potato' (Kainantu Patrol Report Vol 2, No. 2, 1949-50). According to Sorenson (1976:102, 244), sweet potato had just replaced taro as the staple among the Awa language speakers (including Irakia village) at the time of contact. Boyd (1985:124) suggested that sweet potato production at Irakia *increased* during the 1960s in response to an intensification of pig production (Bourke *et al*. 2002:34).

The above-mentioned early patrol report (Kainantu Patrol Reports Vol. 2, 1949-1950, No. 2, 49-50) by Linsey (1949–52a) is especially concise on this matter and bears repeating:

> I reported in a previous patrol report (No. 7, of 48-49) that taro becomes a more prominent feature of native agriculture as one proceeded south from Kainantu to Suwaira, this trend continues right down the eastern side of the Lamari, until, in the lower villages of the Azana [Aziana] Valley, taro becomes almost

the sole item of food, with little yam and no sweet potato.

The consistency of reports by Hays, Boyd, Bourke *et al*., Skinner, and Linsey supports our assessment of subsistence in the Lamari Valley as a gradient in the ratio of sweet potato to yam cultivation beginning in Suwaira and continuing through the Lamari Valley to the Aziana River where, according to early patrol reports, no sweet potato was grown at all. This assessment is described more fully in Supplement 1: Contact History. A similar gradient was observed by ethnographer Ronald Berndt (1962:5), who studied Fore speakers from 1951 to 1953 and wrote in summary: "Staple foods are sweet potato in the north and Taro further south".

Bamboo pipelines were used to irrigate taro gardens throughout Agricultural System 20 (Figures 5a, 5b). Patrol reports indicate they once existed as far north as Obura as late as 1949 (Linsey 1949–52a). Bourke *et al*. (2002) cite they were observed by paleoenvironmental researcher Simon Haberle near Baira, a South Tairora bounded complex on the north side of the Lamari Valley. Patrol Officer Brown observed pipelines on the east side of the Lamari south of Himarata and photographed them in 1953 (Figure 5a). They are also reported by Hays as being used in the Ndumba area some 20 years before 1972 according to older informants. And Boyd (pers. comm. 2020) states that they were last used in Irakia 1993, when an elderly Irakia man built a small system to demonstrate their value to younger men lest they forget the technology. They were reported in the Awa settlements of Tainoraba, Amoraba, Agamusi, and Mobuta in the 1950s (Burge 1954–55; Loving 1976). They were seen in South Fore in the mid-1950s near the west side of the Lamari River below the bounded complexes of Irakia and Tauna (Linsey 1949–52a, b). They were also seen in Tauna and photographed in 1963 in Irakia by Pataki-Schweizer (1980:103; pers. comm. 2018), and Cole observed and filmed them between Mobuta and Amoraba in 1966.

Based on these reports, bamboo pipeline irrigation was used by all Awa bounded complexes. In Awa they were in use in Mobuta into the 1970s and possibly much later. In more isolated areas (Amoraba, Tainoraba, Agamusi) they may continue in use to the present day; there are no recent reports from these bounded complexes. They were used in South Tairora from Obura south to Ndumba and perhaps further, but were abandoned in the middle 1950s, to judge by their absence in patrol reports after 1955 and by Ndumba informants' accounts (Hays 1974). They were used to irrigate taro gardens that sometimes contain banana and sugar cane. Irrigated gardens have never been reported to contain sweet potato, which, unlike taro, thrives in well-drained soil. Their disappearance coincides with the increasing emphasis on sweet potato with similar geographic directionality; it is highly likely that these two trends are reciprocally linked.

It is noted that the boundary of Agricultural System 20 coincides closely with the 1650m contour. This is consistent with the fact that the Awa, living along the Lamari and consuming more taro, have cut much less primary forest above the 1650m contour than their South Tairora neighbors. If we consider the conversion to sweet potato geographically from North Kainantu to the Aziana River area over a 300–350 year period and assume it diffused at a steady rate, we would estimate it arrived at about 250 to 200 BP in South Tairora west of the Ndumba area, in Irakia about 125 BP, and Agamusi in the Aziana River drainage shortly before first contact by administrative patrols in 1955. This estimate is based on the social, physical, and linguistic distances between these locations; however, these dates are little more than informed guesses, and it is not possible to determine if delays in conversion to sweet potato were a function of the rate of technological diffusion, environmental factors, traditions, or magic: Boyd (1975:173) has reported that the Awa of Irakia were extremely cautious about new crops and disturbances of gardens, such that he was prevented from measuring them or bringing his equipment into them and had to reduce his research sample to half of the Irakia gardens on that account. The reason for the delay in conversion to sweet potato is not important in the more inclusive simulations presented here, but the fact of this delay is well established by the available evidence.

Figure 5a. Bamboo pipelines in South Tairora irrigating taro gardens, east bank of upper Lamari Valley, photograph by Brown (2016 [1953]).

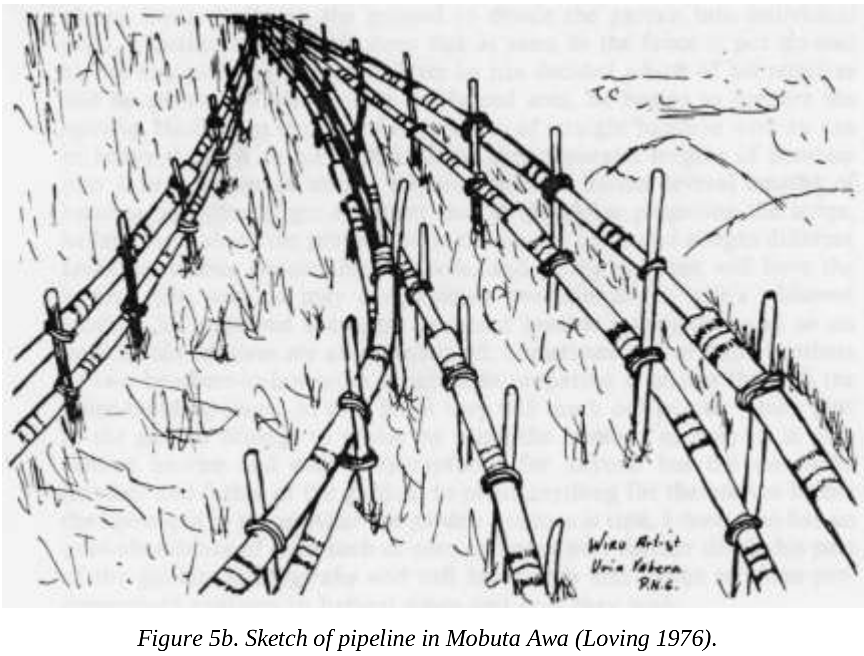

Figure 5b. Sketch of pipeline in Mobuta Awa (Loving 1976).

From the upper to the lower Lamari drainage, there is a visible gradient between the 1650m contour and the forest line (Figure 6). While this gradient exists on both sides of the Lamari, it is easier to see on the south side of the river in the lengthy stretch between Ndumba and Mobuta because the tree line is more regular and clearly defined. This gradient may be due to environmental factors, but it is more likely that it results from the delay in conversion to sweet potato from upper to lower Lamari, since sweet potato promoted the exploitation of higher elevations everywhere in the project area, and especially in South Tairora and Auyana.

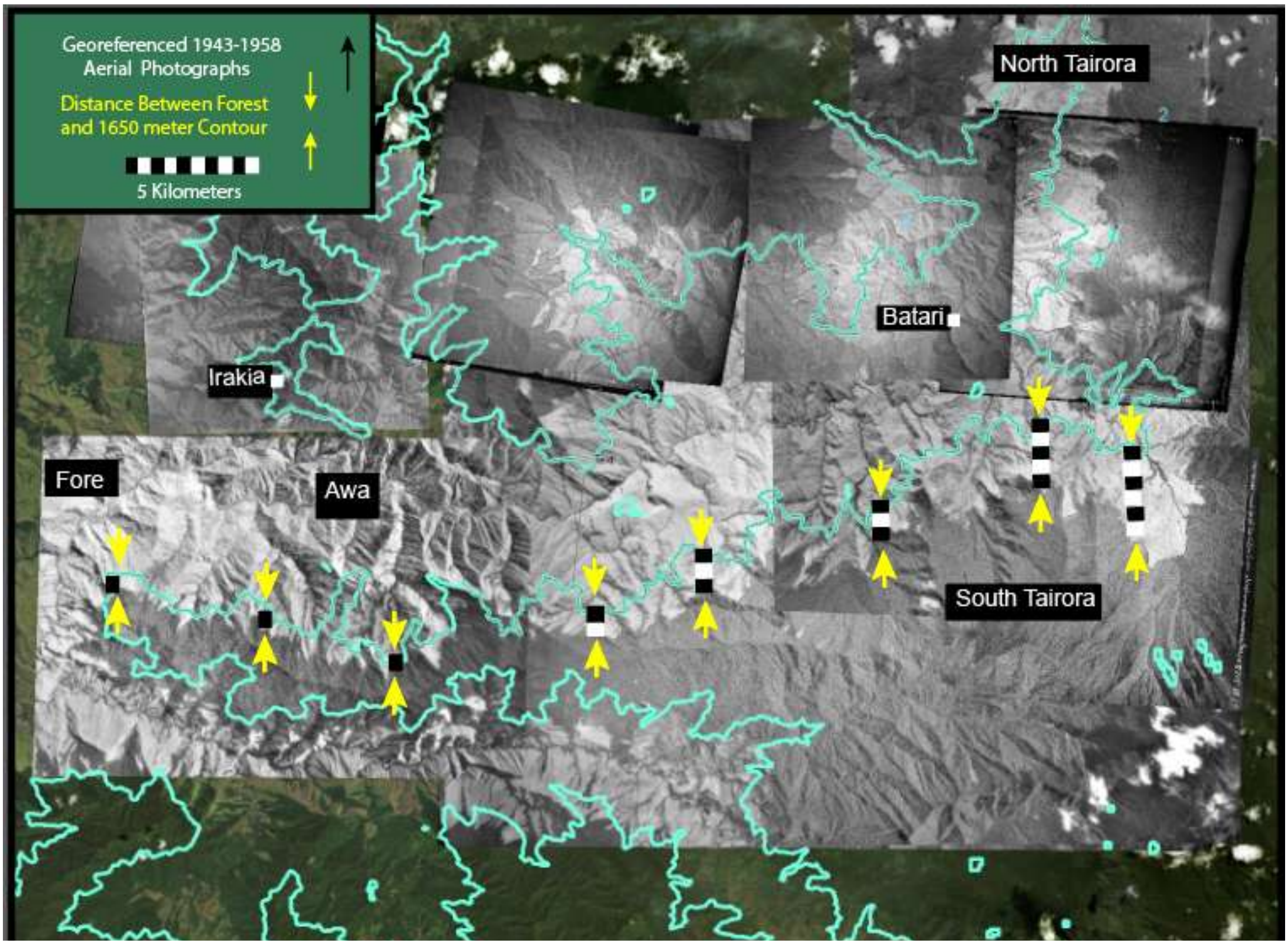

Figure 6. Gradient in distance between the green 1650 m contour (5400 ft) line and forest east to west (Tairora to Awa). Aerial photographs from National Archives and Records Administration, US National Archive, Georeferenced with ArcMap.

Bourke *et al*. (2002:1-106) classify the area that lies roughly above the 1600m contour and below primary forest as Agricultural System 5. This system is distinguished from nearby System 20 by differences in fallow vegetation, fallow period, and cropping period rather than by staple crop. The Dominant Staple for this system is stated as sweet potato with no Subdominant Staples, and with banana, sweet potato, taro (*Colocasia*), and yam (*D. alata*) deemed "Staples Present". Irakia, which lies near the 1600m contour, is included in the description of this system. This may seem puzzling since Bourke *et al*. clearly state that taro, not sweet potato, is the Dominant Staple there. Nevertheless, the ASP typology is based on agricultural methods, not type of staple, and the result is this anomaly. Agriculture System 5 does serve as a description of other cleared areas above 1600m that are now devoted largely to sweet potato gardening and illustrates Hays's observation from informants that taro does not do well at higher altitudes. We can safely say that for the most part, System 5 represents the extension of agriculture above the pre-ipomoean limit for sweet potato, which has become the major staple in the South Tairora part of this zone.

Moving north of Irakia and the Lamari Valley, Auyana is characterized by Bourke *et al*. (2002) as Agriculture System 6, in which the Dominant Staple is again sweet potato supplemented by small amounts of yam and taro. Accordingly, "taro and yam are grown together in separate gardens from sweet potato. These are planted only once before fallowing. *D. alata* is the most common species of yam, but *D. bulbifera* and *D. pentaphylla* are also grown." The anthropologist Sterling Robbins measured food intake for five families during his first residence in Auyana in 1962–1963, and sweet potato was the only significant tuber recorded during this time. Taro was mentioned as being used primarily for ceremonial occasions, and yam did not appear in his data as a significant part of the Auyana diet (Robbins 1982:47-49).

Again, it may seem odd that Tauna, an Awa bounded complex in which taro was the Dominant Staple and in which bamboo irrigation was practiced until recently, is included in Bourke *et al.*'s description of System 6. It must be remembered again that Bourke *et al.*'s typology is based on gardening practices, not staples, and the last time bamboo irrigation was seen in Tauna was in 1963 by Pataki (Pataki-Schweizer 1980:93). It is also possible that Tauna is further along in adopting European foods and sweet potato than Irakia, insofar as it is closer to Auyana and has traditionally been linked to Fore and Auyana through trade.

Auyana territory above 1650m resembles South Tairora insofar as the primary forest has been cleared over a large extent to about 2200m for cultivation of sweet potato. Unlike South Tairora, which is part of the Lamari Valley gradient, Auyana represents an abrupt break from the taro/yam subsistence of its Awa neighbor. The soil may also be richer in Auyana, and there is a basin in the southernmost extent below 1650m (Robbins 1982). In our model we envision Auyana as having been populated by migration from Awa in pre-ipomoean times, since the language is closely related to Awa and especially Gadsup in the Kainantu Language Family. Its moist and sometime soggy basin would have been ideal for taro with no need for irrigation. There are also good topographical reasons to support the introduction of sweet potato from the west through Fore. The terrain in the south is less severe and there is a broad gap in the Kratke Range between Auyana and Fore several kilometers north of Okapa. Indeed, Skinner used this route for his first patrol into Awa in 1947, as did many subsequent patrols into Awa and the Aziana Valley. The Fore have been aggressive in their planting of sweet potato, and their voracious consumption of the forest between their northern area and their border zone immediately adjacent to western Auyana makes it a likely route for diffusion of sweet potato technology (Sorenson 1976). The diffusion route from the northern Kamano basin is geographically open, and much of the distance from north to south is through a single language group. It is feasible that sweet potato arrived through Fore to the southern boundary zone with Auyana by 250 BP.

Robbins devotes five pages of his 1982 monograph to the subject of gardening practices in the area of the Auyana (Asempa) bounded complex. He commented that the optimal allocation of garden space between forest (primary and secondary) and grassland was a 1:1 ratio (Robbins 1982:51–56). In an actual garden count, he found 74 (38.7%) out of 191 gardens were taken from primary forests. Unfortunately, the size of the gardens was not measured, and no mention was made of a significant difference in size between forest and grassland plots. The western Auyana bounded complex lies near the base of two valleys that become narrower with increasing elevation. It is likely that the ratio of primary forest gardens to grassland and secondary growth gardens increased as elevation increased in response to population pressure after full conversion to sweet potato. This is borne out by the authors' measurements based on georeferenced aerials photographs from 1957 and 1958 (see below, Table 3). This leads us to consider a 1:1 ratio of primary forest to be credible as a maximum for forest clearance rate after initial clearance following a fission and migration event when high forest-to-grassland ratios are required during the first years. These ratios would necessarily be up to 100% initially since there would be no grassland or secondary fallow available during the first five to 15 years, depending on the length of the fallow cycle and the number of years a new garden from primary forest was used before the first fallow period. In addition, the gardening practices Robbins describes are similar to those described by Sorenson (1976) in his text and photographic survey, which leads us to believe that sweet potato technology was introduced to Auyana from the west rather than from the parental bounded complexes of Tauna and Irakia, which are adjacent to the immediate south of Auyana. In these communities, much greater use is made of fallowed land, with less than 5% of garden area claimed from primary forest based on GIS surveys using aerial photographs from 1943 and 1958. The Auyana did not use bamboo irrigation at the time of first contact and, like the Fore, adapted readily to Western crops and had converted almost entirely to steel tools by the time of Robbins's research in 1962–63.

In summary, the APS database of gardening practices and land use captures many characteristics of the project area, including the gradient in taro to sweet potato ratio, the progressive disappearance of bamboo irrigation technology from east to west and north to south over time, and the elevation limits for taro around the 1650m contour. These trends support our conclusion that conversion to sweet potato took place earlier in the upper Lamari Valley than in the lower and that the most likely reason for this is that, like the impacts of Western contact, transmission of ipomoean technology was delayed in reaching these remote and relatively isolated areas: the more remote, the more delayed. Once available in Awa, the conversion to sweet potato may have been further delayed by other sociocultural and environmental factors (Figure 7).

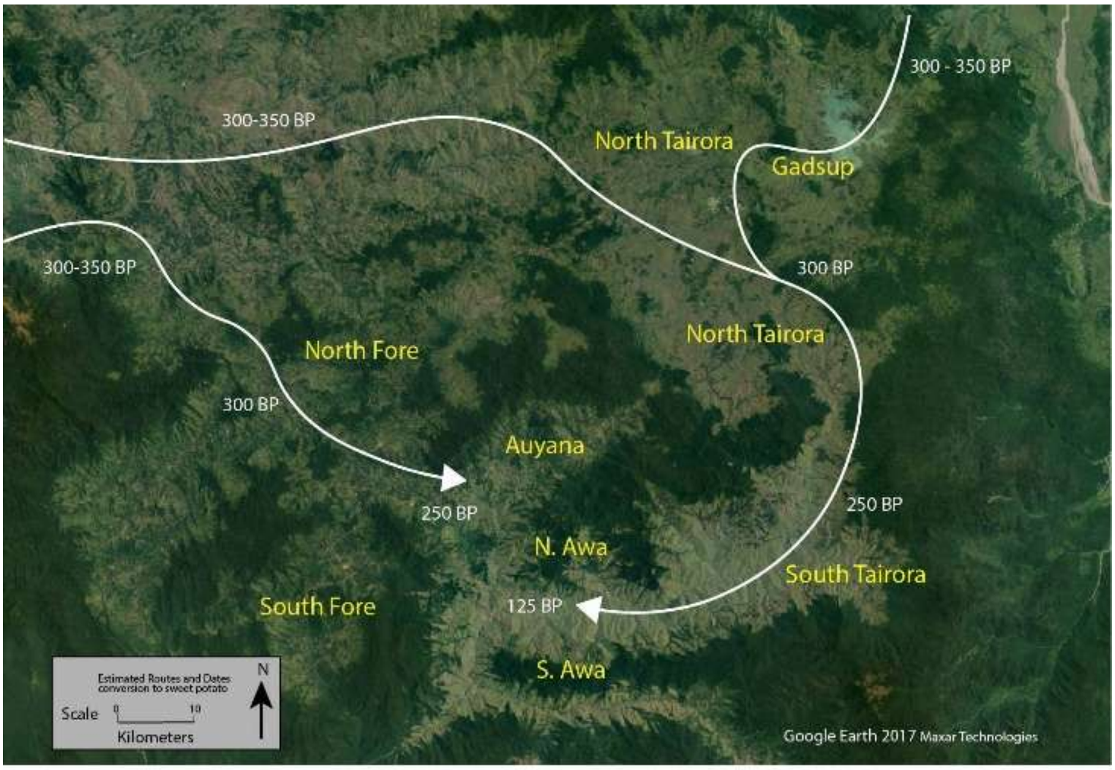

Figure 7. This map shows most likely routes and dates for diffusion of sweet potato technology into the project area. Base map:Google Earth 2017 Maxar Techologies. Overlay source: The authors.

This assessment motivated our project to use these remote areas as a window through which we might see how people lived in the pre-ipomoean past, and to help us understand the archaeological and paleoenvironmental evidence from Noraikora, NFB, Aibura, and Batari to reconstruct the prehistory of the study area. It would of course be ideal to have documentation from the most remote regions in the Aziana Valley where, according to reports, people lived without sweet potato altogether at the time of first contact. In the absence of quantitative data from this region, we draw on Boyd's (1975) dissertation, which was based on Irakia in 1971–72. His work has a wealth of detail, including physical measurement of nine garden types and their outputs, measurements of consumption for the staples grown, calculation of production units, and other measures of the Irakia subsistence economy. Boyd's work is supplemented by the work of Hays in the upper Lamari Valley (1971–72), Robbins in Auyana (1962–64), and Loving in Mobuta (1959 and on, intermittently), in addition to the area and group overviews, maps, census data, and statistics compiled from Pataki's work in the study area in 1962–63 and archaeological research by Cole, who spent six weeks in Auyana, Awa, and South Tairora near Ndumba in 1966–67.

THE IRAKIA AWA: A MODEL OF PRE-IPOMOEAN ECONOMY

Earlier research and preliminary stages of the present research drew our attention to the Awa. The Awa and their bounded complexes were studied by Pataki in 1962–63, Phillip Newman in 1964–65, David Hayano (1990) in 1969–70, and David Boyd in 1971–72 with subsequent visits to 1993; Awa was surveyed for archaeology sites by Cole in 1966. At the time of their first contact by Australian patrols in 1947, the Awa practiced a taro-yam economy and we saw their economy as a potential model for subsistence before the introduction of sweet potato (*Ipomoea batatas*) to New Guinea. The idea that taro and to a lesser degree yam, supplemented with various cultigens and forest products, formed the basic subsistence staples prior to the introduction of sweet potato in the Central Highland of New Guinea is accepted by most New Guinea specialists (Brookfield and White 1968; Strathern *et al*. 2002; Ballard 2005; Bourke 2005a, 2005b; Boyd 2005; Ploeg 2005; Swaddling and Hide 2005; Wiessner 2005).

To find an alternative model, especially for the Eastern Highlands, one must harken back to Watson's early publication (1965) that proposed a hunting and gathering economy immediately prior to the ipomoean revolution as one of several possibilities. Watson's hunting and gathering construct was later undermined by Haberle's paleoenvironmental research in the Arona valley and Noraikora swamp, the discovery of early ceramics at NFB circa ~3200 BP (Huff 2016b), and evidence for horticulture at Kuk in the Western Highlands between ~6,000 and ~9000 BP. Since Watson's conjecture, no other credible alternative to the taro-yam combination has been proposed. *Pueraria lobata* (a variety of kudzu with extremely large tubers) may have had minor prominence as a supplemental crop in prehistoric times, notwithstanding the amount of cooking and/or pounding required to make it palatable. Yam cultivation is far more widely practiced as a secondary staple. It is an ancient crop, easy to prepare, adaptable to diverse environments, and, like taro, holds a privileged place in the ritual life of many highland and lowland societies. The use of Awa economy as an example of this early taro/yam–based subsistence economy is therefore aligned with the contemporary consensus concerning the sequence of horticultural technologies, that is: 1) foraging; 2) taro/yam horticulture; 3) sweet potato as staple; and 4) sweet potato plus impacts from the incipient global market economy.

In adopting this model for the pre-ipomoean economy at the time of sweet potato's introduction, we do not ignore the probability that pre-ipomoean horticultural technology changed over the time encompassed by our projections. We might imagine that the early pre-ipomoean adaptation depended more heavily on foraging and less on agriculture and intensified as the result of innovations over time. One such innovation might have been the reuse of fallow land, which is now practiced by Awa and other farmers in the study area over a ten- to twenty-year rotation cycle. Taking this into account would result in scenarios in which the rate of primary forest clearing was high at the outset and gradually (or rapidly) declined over time. Another intensification might be the introduction of casuarina for firewood, fencing, and soil improvement during the fallow cycle beginning in the northern basins by about 600 BP and reaching Awa close to the time of contact with the West (Haberle 2003:156). In this regard, the Awa depended heavily on bamboo for fencing and recently for house construction in 1956, as observed by Loving (1976). Bamboo pipeline irrigation is yet another intensification. While it may have been used throughout the Eastern Highlands in pre-ipomoean times, it may also have been independently developed in South Tairora and/or Awa territory as migrants adapted to much steeper terrain. Boyd (pers. comm. 2019) has pointed out, “This movement of water to pockets of arable land would have facilitated increased production of taro”. It is, however, likely that its positive benefit to productivity was outweighed in whole or part by the steepness of slopes bordering the Lamari River in Agricultural System 20 south of Aibura.

The Awa Model

The Ilakia bounded complex and Awa economy were documented by Boyd, who studied the Awa bounded complex (1975; Pataki-Schweizer 1980:31–37). The Awa, as typified by the Irakia of this period, are unique among their neighbors in a number of features:

1. Unlike other Kainantu Language Family members, the Awa dedicate more land to taro-yam gardens than sweet potato. In 1971–72 the land-use ratio of taro/yam gardens to sweet potato gardens was 58% to 37%, and the production ratio of taro/yam to sweet potato was 60% to 40% (Boyd 1975).
2. Until the early 1990s, the Awa employed a remarkable form of irrigation using bamboo pipes to convey water over rugged terrain to taro gardens from upland sources over distances of up to three miles, or five km (Figure 5).
3. The Awa cut little primary forest and rarely did so above 1650m. This was reported by Boyd for the Irakia and confirmed for both Tauna and Irakia by our analysis of 1943 USAF aerial photographs using ArcMap.
4. The Awa are the smallest language group in the project area, with a reported 1963 population of 1374 as compared with Gadsup (7383), Tairora (10,751), and Auyana (4210) (Pataki-Schweizer 1980). Of the 1374 Awa, 1168 live in the project area of the Lamari watershed, and this is the number used in all following calculations. The remaining 206 Awa speakers of Agamusi live over a formidable ridge south of the Lamari River in the Aziana River watershed.
5. In 1972–73, the Irakia Awa raised fewer pigs (0.6 per person in 1971–72) than other Kainantu language groups, and their exchange systems were much smaller in scale than the ceremonial exchange systems of groups to their west, including most members of the Gorokan, Chimbu-Waghi, and Engan language families. Furthermore, whereas pigs thrive on raw sweet potato, taro and yam must be cooked to make them palatable as fodder for swine. Considering this and the high esteem and ritual significance of taro and yam, we estimate pig husbandry to be less intense and herds to be much smaller in pre-ipomoean times, with more dependence on semi-feral grazing supplemented with food scraps used to bond otherwise feral pigs to humans and their habitats.

The Development of a Pre-Ipomoean Model

The creation of our pre-ipomoean model required three revisions of Boyd’s data to compensate for differences in annual land requirement between the 1971–72 Irakia economy in which 40% of tubers produced by humans in 1971–72 was sweet potato, and a pre-ipomoean economy in which there was no sweet potato production. This required the use of three equations that adjusted the annual cultivated land required for Boyd’s sample population of 117 to the annual cultivated land required for a pre-ipomoean subsistence; that is, a taro/yam-based subsistence with an estimated half the number of pigs and no sweet potato. These calculations can be found in the Supplemental Data 3. They are summarized in the steps below:

1. Our first revision reduces the amount of sweet potato grown as pig food in 1971–72 by 20% to estimate the land use in pre-ipomoean times more accurately. It recalculates the annual garden land requirement to match that reduction.
2. The second adjustment uses the productivity difference between sweet potato and taro/yam gardens to reduce the area of taro and yam gardens required to

compensate for the absence of sweet potato.

3. This result is then adjusted to reflect a slightly higher energy yield in Kcals for cooked sweet potato over a cooked yam taro mix of 80% taro and 20% yam, approximating the Irakia blend in 1971–72.
4. The application of these adjustments reduced the total amount of land required to maintain a taro/yam subsistence for the 117 individuals from 7.851 ha to 6.906 (6.9055) ha.
5. Boyd (1975) measured the Irakia garden work force as 69.8 production units (PU) for his sample population of 117. This means that each PU must cultivate 989 m^2 of land to produce the nutritional requirement for Boyd's sample population. In addition, the number of PUs for any trial population can be calculated using the ratio 69.8/117 = 59.7%. Boyd determined productions units by summing production factors assigned to age classes without regard to gender (Table 1).

Table 1. Production factors summed to determine the number of production units in Boyd's Irakia data.

Age class	Production factor
Birth through 10 years	0
11 through 14 years	0.3
15 years through married	0.5
Married to elderly	1
Elderly (non-productive)	0

6. Thus, 6.9055 ha = 69,055m^2; $\frac{69,055}{69.8}$ = 989.3 m^2/PU, the amount of land each PU must clear per annum.
7. And accordingly, $\frac{69.8}{117}$ = 59.7% , the percentage of PUs required for subsistence for a pre-ipomoean simulated population of 117.

Population Density

The average density for all Awa bounded complexes within the Lamari watershed for 1962–63 is 9.6 persons per square kilometer of grassland, based on GIS calculation of areas below the 1650 m contour and population estimates from 1962–63 (Hays 1974; Boyd 1975; Pataki-Schweizer 1980). It has the lowest population density overall for major language groups in the Tairora Language Sub-family. This density was reached with the addition of sweet potato for an estimated 187 years since the introduction of or conversion to sweet potato, a period in which population growth rates for the project area increase considerably.

In our simulations, Vector 1 attained the best fit for all constraints with the highest pre-ipomoean growth rate per annum of 0.00062% (Table 8 below) and 0.00117% for Vector 3 (Table 10). In 1963, after 187 years, the Awa growth rate is estimated from patrol reports and data provided by Boyd (1975) and Pataki-Schweizer (1980) at 1.50%. During the same period, grassland area in the Awa expanded approximately 5.8 km^2 (5.7%) above the 1650m contour. Based on these simulations, Awa pre-ipomoean population density was less than 9.6/km^2, yet we have no way of calculating the lowest density possible beyond the values these simulations provide. We know that Awa density was considerably lower but not how low the population growth rate and the resulting density could have been without disrupting pre-ipomoean social and economic life to the point of extinction, which would also appear to have been a real possibility for the very early groups.

The language group with the lowest population density in this environment is the South Fore dialect of Ilesa, which includes the dialect of Abomatasa. This population occupies the west bank of the Puburamba River adjacent to the Awa bounded complexes of Tauna, Irakia, and Mobuta. Its density is estimated at 5.4/km^2 by Sorenson, who does not cite his source. Immediately to the south of Ilesa is the territory of the Pamusa Fore dialect with a density of 5.7/km^2, also with no source cited (Sorenson 1976:21). Glass (1969) gives 6.9/km^2 as the density for Pamusa in Fore and cites the 1962 Department of Native Affairs Census and Village Directory of TPNG (the Territory of Papua and New Guinea, the UN protectorate status administered by Australia before independence in 1975). Such discrepancies are not surprising and do not negate Sorenson's figure, since population numbers in South Fore were impacted by the neurodegenerative disease of kuru, especially for very young and much older females, and other causes; e.g., Patrol Officer M.D. Allen (1961–62) provides a well-documented report of a drop in population growth rate in nearby Gimi from 3.6% in 1961 to 1.1% in 1962 due to child death from pneumonia.

The Ilesa inhabit an area in which bamboo irrigation systems have been reported (Loving 1976:542). They occupy the southern extreme of South Fore and were likely to have recently converted to sweet potato. Sorenson (1976:22) suggests that speakers of the Ilesa and Abomatasa dialects on the west side of the Puburamba river were migrants from the Lamari Valley. This is possible since they are the only Fore speakers who are conversant with people of Mobuta and Irakia bounded complexes who speak two different dialects of Awa. Another explanation is that they are bilingual trading partners of these bounded complexes.

The existence of populations adjacent to Awa in a similar short–grass environment, equally isolated and with indicated population densities of some 5.0/km^2, has led us to accept 5.0/km^2 as the lowest value for density in the pre-ipomoean date ranges for all our simulations; in evaluating this constraint, we average the four lowest density values. As it turned out after hundreds of trials for Vector 1 and 3, the best-fit simulations tend to center around 5, and those that fall below 5.0 often miss the 600 BP year constraint for population or cleared area. The simulation in Table 6 is an example. Its population growth rate was raised from 0.00033 to 0.00053 to meet the density, population, and area constraints at 600 years BP (see Table 7).

SIMULATION MODELS

This study utilizes dynamic simulation modeling to approximate scenarios of demographic and environmental change. This methodology is used in various sciences to explore properties of systems not otherwise apparent or accessible through descriptive methods or analytical statistics (Mithen and Reed 2002; Gilbert and Troitzsch 2005; Nikita and Nikita 2005; Romanowska 2015). Simulations in this report are computed from parameters derived from Boyd's and others' field research and operator variables. Operator variables are entered into simulator spreadsheets by researchers as they run trials intended to meet constraints. Constraints are reference points for computational trials that model and estimate human ecological statuses over time, i.e., they are conditions for simulations that either meet or miss within a reasonable margin of error (<2.0%). These constraints specify population size, density, and forest clearance area estimations derived from our Irakia-based, pre-ipomoean model and from post-ipomoean sources using ethnographic fieldwork, patrol reports, and georeferenced aerial photographs from 1943 to 1968. The purpose of this process is to determine best-fit simulations for scenarios of population increase and growth rate, grassland areas above 1650m elevation, and forest clearance rates. By "best fit," we mean simulations that best meet or approximate constraints (see immediately below). These constraints are formulated from data sources to describe population movements and environmental changes at specific times between 4200 BP and the present.

Pre-Ipomoean Constraints

Since the people of Awa and of South Tairora, using 1971–72 ethnographic sources as our reference, strongly preferred a zone at or below approximately 1650 meters for taro production, we assume that prior to the introduction of sweet potato, the entire Lamari Valley was cleared, farmed, and burned below that altitude, leaving the pre-ipomoean forest line at or about 1650m by the end of pre-ipomoean times (Hays 1974; Boyd 1975).

We further assume that fission and diffusion occurred when land was needed to resolve internal and external tensions and hostilities, soil exhaustion, or land shortage within local groups. This led through repetition to extension of migration frontiers into adjacent primary forests. We therefore used GIS to estimate the grassland area below the 1650m contour and between key markers (e.g., Noraikora to Aibura; Aibura to Batari; Batari to the border zone with Awa; Awa/Auyana border zone to the Auyana 1650m contour). We take these area measurements to represent the altitudinal limit of cultivation in the pre-ipomoean period, including the agricultural practices reported by Boyd for Irakia in 1971–72 and T. Hays for Ndumba in South Tairora in 1972. They are as follows:

1. Aibura to Batari: 24 km^2 to 48 km^2 for the 1500m to 1650m contours, respectively*
2 Batari to Tairora border zone: 132 km^2 for the 1650m contour
3 Tairora/Awa border zone to Awa/ Auyana border zone: 123 km^2 for the 1650m contour
4 Awa/Auyana border zone to all of Auyana: 47.4 km^2 for the 1650m contour
5. Total area for 1-4 above: 350 km^2 for the 1650m contour
6. Density: ratio of population to grassland of 5.0 or greater.

   * Two estimates were used for the Aibura to Batari constraint due to the steepness of the terrain in this area. It is likely that much of the area between these markers is too steep for gardening with gardening restricted to narrow margins below 1500m along the Lamari River.

Post-Ipomoean Constraints

A set of constraints for population sizes and grasslands in the post-ipomoean period were also determined. These constraints are:

1. A 1963 Awa population of 1146 after subtracting 206 for the Agamusi Awa bounded complex outside the project area
2 A 1963 study area population of 11,155
3 Study area grassland extent from 1943–1969 GIS measurements of 527 km^2
4 A 1963 Auyana population of 4210
5. A 1963 Auyana grassland extent of 101 km^2
6. A 600 BP forest clearance area of 303 km^2 at the Awa/Auyana border zone.

Parameters

Parameters in our simulations are derived from Boyd's (1975:132–168) descriptions of Irakia economy:

1. An agricultural workforce with production units of 59.7 person-units per 100 persons.
2 Each production unit cultivates 989 m^2 (slightly less than 32m x 32m) of land per year in pre-ipomoean times and 1023 m^2 after the introduction of sweet potato. Both figures are derived from Boyd's research data.
3 The area (A) cultivated per year by a population (P) was determined by the formula $A = P \times 0.596 \times 989\ m^2$.

Operator Variables

Other simulation inputs are the operator-controlled input variables. These include:

1. Size of founding population. This is consistent throughout at 325 and is based on the mean size of the smaller bounded complexes times 2. At the time of contact an approximately equal number of settlements were situated on both sides of the Lamari River. We presume this pattern has existed throughout the modeled dispersal periods.
2 The percentage of primary forest cleared per year.
3 The starting date for the dispersal event or events (3500 BP, 2000 BP, 1000 BP).
4 Population growth rates prior to 250 BP. Later dates are fixed and based on ethnographic sources and patrol reports as summarized by Pataki-Schweizer (1980):

   300 BP operator input variable
   200 BP operator input variable
   100 BP fixed, 1.25% interpolated from ethnographies
   0 BP fixed, 1.50% interpolated from ethnographies
   1963 BP fixed, 2.20% from ethnographies (Pataki-Schweizer 1980; Boyd 1975)
   1972 BP fixed, 2.50% from ethnographies (Hays 1974).

RESEARCH DATA

Our research also utilizes data from archaeological and paleoecological sites in the project area. Figure 8 summarizes sequences of the past 4200 years from four sites near and within the Lamari basin in the study area. From left to right, these sources include cores from Noraikora swamp sampled by Haberle (1996); open site NFB on the eastern perimeter of the swamp excavated by Cole (1996; Watson and Cole 1977); and Aibura and Batari caves excavated by White (1972). These sites lie along the assumed dispersal route (Figure 3). Other possible routes were examined and excluded by virtue of geography, altitude, longer crop cycles for taro and yam (11–12 months), and ethnohistorical narratives.

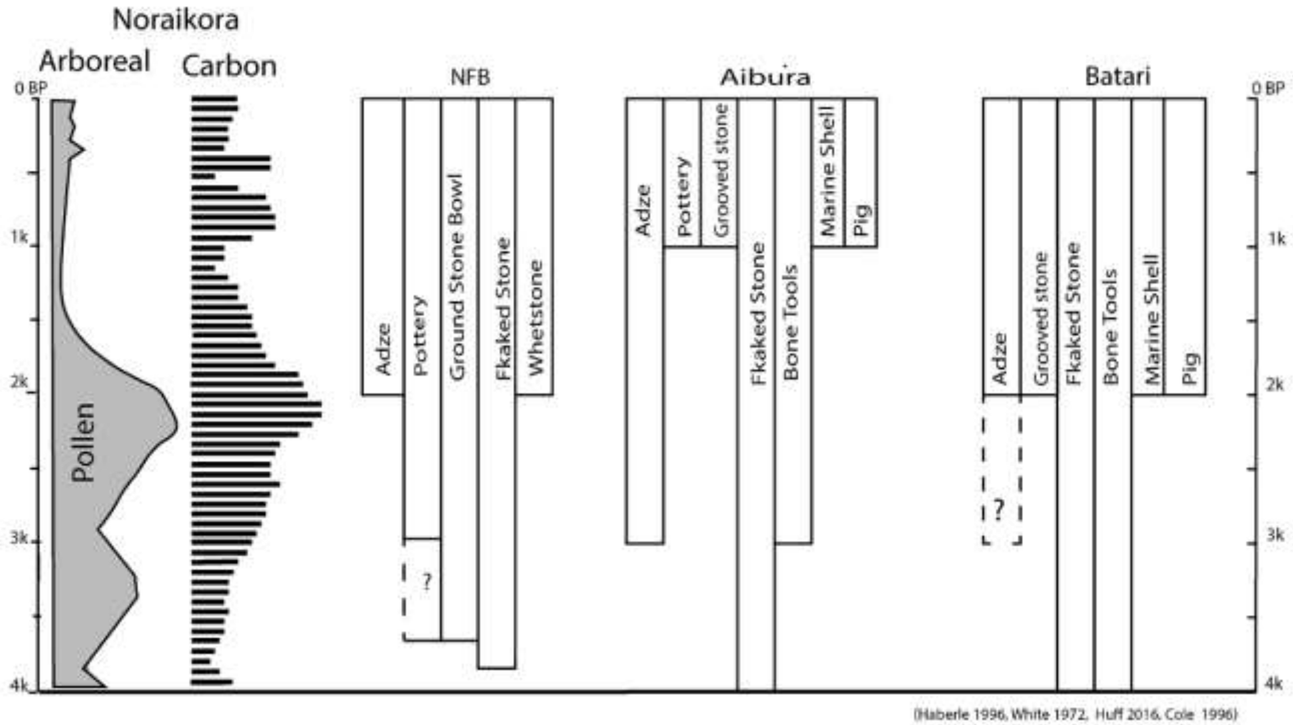

Figure 8. Paleoecological and archaeological sites and data from Haberle (1996), White (1972), Huff (2016b), Cole (1996). Source of illustration: The authors following Haberle (1996) and White (1972).

These four sites are also represented in Figure 9, where they are replaced with vertical black lines. The first line (from left to right) combines carbon dates and events from NFB with Noraikora Swamp core data. Definitive C_{14} dates are flagged with black dots, and interpolated dates are shown by blue bars. The x-axis is scaled for deforestation in square kilometers below the 1650m contour, and the y-axis shows intervals for time in years BP. The introduction of sweet potato is indicated by the dashed blue line at the top of Figure 9.

The three orange lines in Figure 9 (V1, V3, V5) represent potential population dispersal events with settlement and deforestation below the 1650m contour. Vectors V2, V4, and V6 were eliminated as their slopes are too steep (meaning the rate of dispersal is too slow) to reach Awa before contact (see Figure 10). Reports from two ethnographic sources indicate that initial pioneers, like the present Awa and South Tairora speakers prior to their conversion to sweet potato, did not clear land to plant taro and yam above the 1650m contour (Hays 1974; Boyd 1975). Low soil fertility, low rainfall, and steep terrain may be contributing factors (Brookfield 1964; McAlpine *et al*. 1983). Grasslands above the 1650m contour in South Tairora and Auyana are therefore largely the result of sweet potato cultivation during the past 250 years. This may not be the case in other highland regions where taro and yam have been grown above 1800m with adequate yields (Bourke 2005b). In Figure 9, the *terminus ad quem* date (the most recent possible date of arrival) was determined by preliminary simulations and was found to lie between 400 and 600 BP (see discussion below and Tables 13a and Table 13b). In addition, analysis of archaeological data from surface collections in the Auyana basin favors the earlier date of 600 BP (Figures 11, 12, and 13).

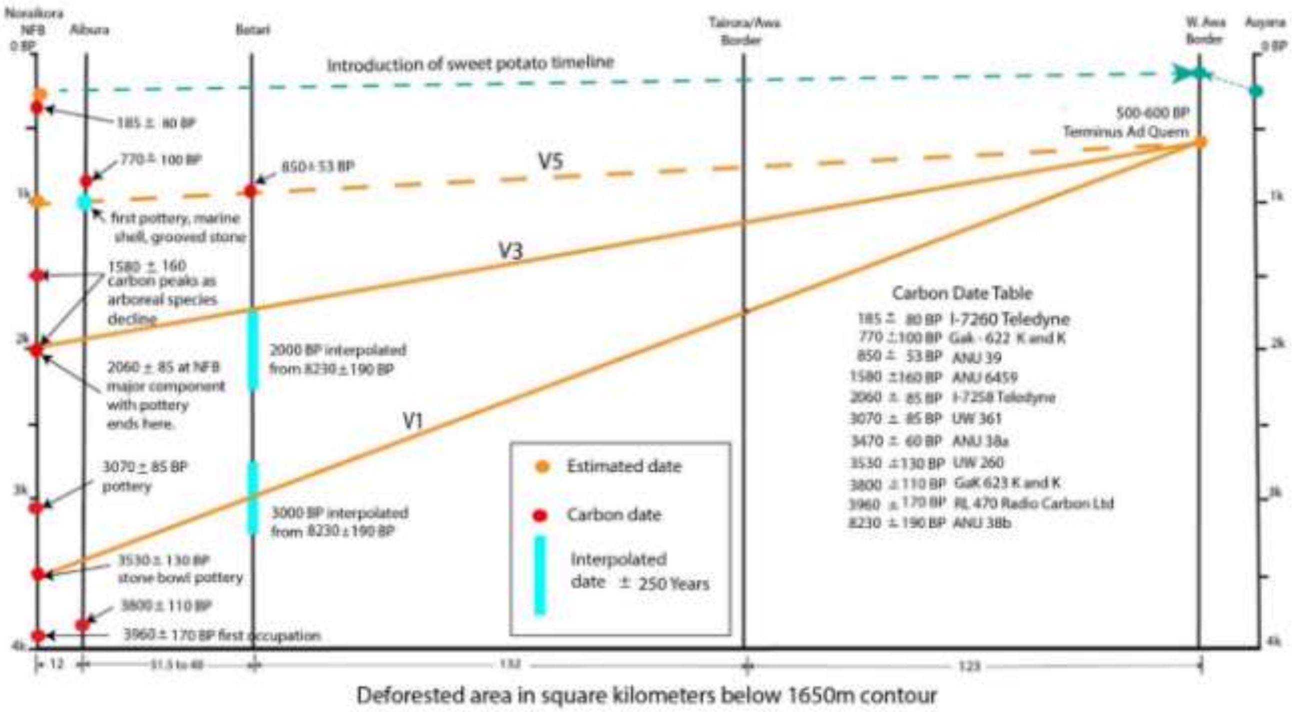

Figure 9. Vectors representing potential dispersal events with settlement and deforestation below the 1650m contour. Terminus ad quem = *estimate of most recent date possible for arrival at the Awa/Auyana boarder zone based on trials and archaeological evidence. Source: The Authors.*

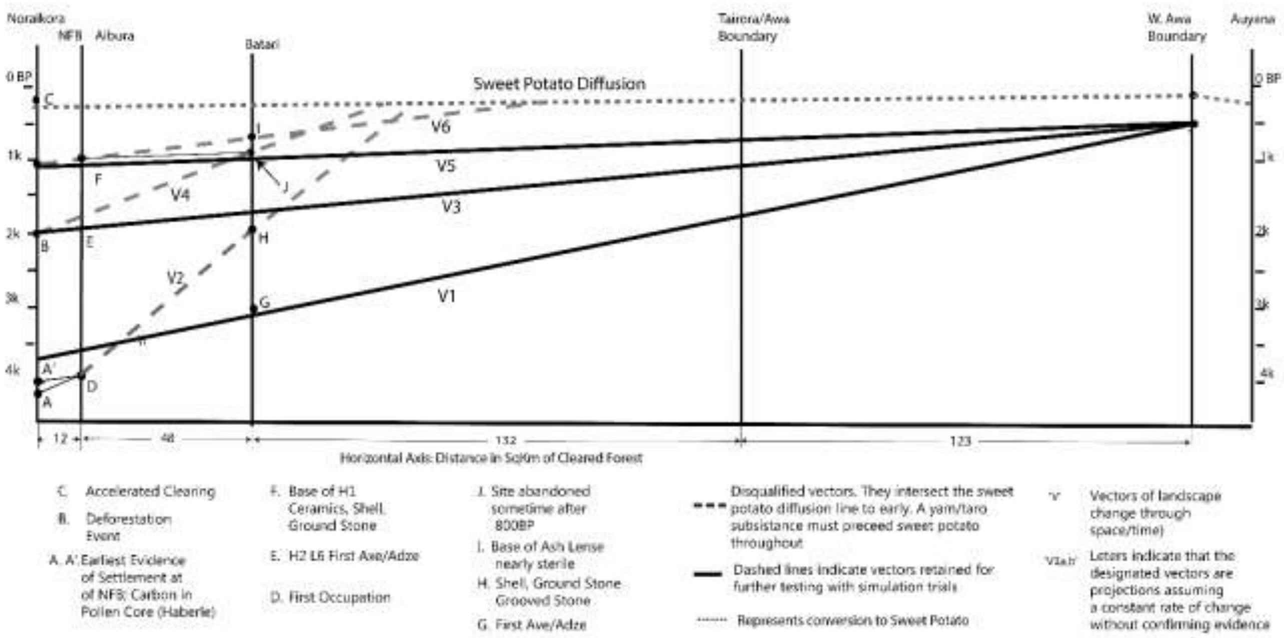

Figure 10. Showing the disqualification of Vectors V2, V4, and V6 (dashed lines), which intersect the sweet potato diffusion timeline before the arrival of taro and yam at the Tairora/Awa boundary Zone. Source: The authors.

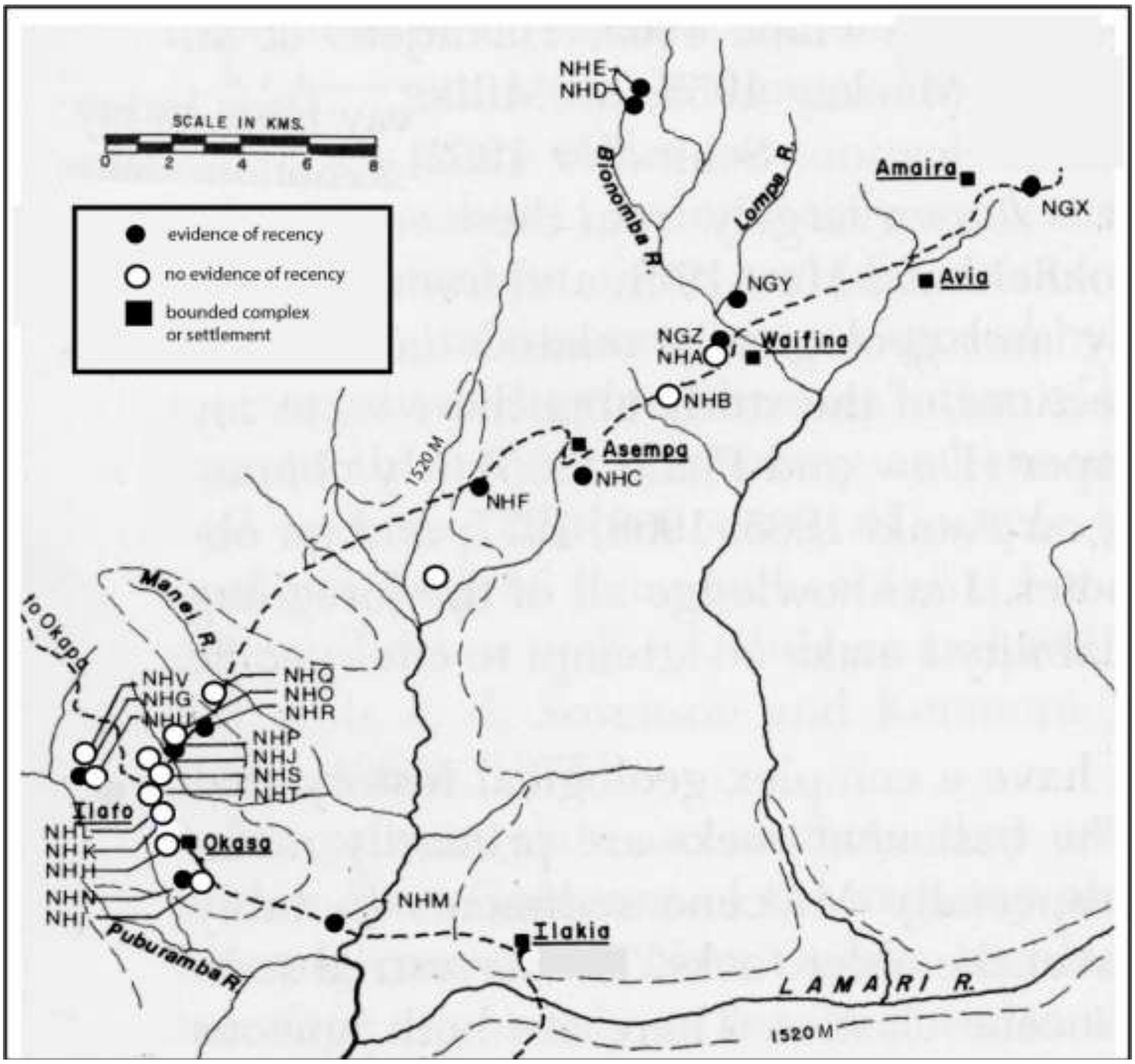

Figure 11. Map of sites in the Auyana basin and uplands. Data from Cole's Field Report 1a, and site survey forms, 1963, archive of the Cole Collection, Burke Museum of Natural History and Culture.

AUYANA: THE END OF THE KAINANTU MIGRATION

The Auyana basin and uplands were the last territory colonized by speakers of the Kainantu Sub-family. Ethnohistorical data obtained by Pataki (1965) in 1962–63 and Cole in 1966–67 include coherent accounts by Auyana informants of migration and deforestation from Waipina to Amaira (Figure 10). These accounts include named ancestors and site locations. Many of the sites referenced were surveyed by Cole and found to contain lithics and surface features consistent with informant narratives (Watson and Cole 1977). Pataki-Schweizer (1980) also obtained accounts of earlier movements from three named sites of origin along the southern border zone of Auyana. According to informants, fission and migrations from these sites produced three stocks that gave rise to the lineages and bounded complexes that comprised the Auyana population in 1962–63. It is clear from these accounts that populations have moved up the basin in a northeasterly direction in what Pataki-Schweizer (1980:78) described as a "dendritic fission," where splitting and serial migrations may reflect demographic pressure combined with flight due to warfare or raiding. Pataki's ethnohistorical data are summarized in Table 2. This table elaborates on the stock markers given in Pataki-Schweizer's 1980 monograph. The topography, size, and history of fission for Auyana made generic information more readily available, with some indication of relative time depths.

Figure 12. Stratified deposits at Kafiavana at the dripline (photo by Cole 1964).

This appraisal is supported by the distribution of archaeological sites recorded by Cole in his Auyana survey (Figure 10). His survey followed the track from Amaira, through Waisempa to the southern border zones, which Auyana now shares with Awa and Fore (Figure 2). In the area above 1500m, Cole recorded nine sites, seven of which contained evidence of recent occupation, estimated to be within the last 100 years based on the decomposition of wooden house posts and the existence of post-contact features such as latrines and open cooking pits (not yet filled with slump and/or overgrown). Below the 1500m contour, 16 sites were found, including five with evidence of recency. The distribution of these sites is again consistent with the ethnohistorical data indicating recent migration from the lower altitude southern border zones.

Table 2. Reconstruction of Auyana ethnohistory from origin sites to historic bounded complexes in 1962–63.*

Bounded Complex (Major Settlement)	Traditional Origin Site	Initial Site	Dispersal Site	Established Site	Recent Sites
Asempa	1	A	1		
Omuna	1	A	1	a	
Sinkura	1	A	2		
Kowiunda	1	A	2	a	
Waisampa	1	A	3	a	
Amaira	1	A	3	a	1
Avia	1	A	3	b	
Nankona	1	A	4		
Waifina	1	A	5		
Avikara	1	A	6		
Anofafa	1	B	1		
Kawaimpa	1	C	1		
Asuwairapa	1	C	1	a	
Warapa	1	C	2		
Arora	2	A	1		
Sefuna	2	B	1		
Indona	3	A	1		
	Generator	**Stock**	**Family**	**Bounded Complex**	**Bounded Complex**

**Population dispersal site numbers are in probable temporal sequence (earliest to latest) and of two or more generations in depth. "Recent Site" means within one generation (approximately 20 to 25 years). A blank under "Established Site" indicates "same site as preceding entry." Presumably, most of these fission and population disbursal events occurred after the introduction of sweet potato (Pataki-Schweizer 1980, Appendix 4:142).*

Finally, a comparison of aerial photographs from 1957 with 2017 Landsat imagery shows that 20.6 km^2 of primary forest (an increase of 48.6%) was removed between these dates. Most of this deforestation occurred above 1800m in Auyana's northeastern uplands (Table 3), of which Amaira is an outlier in this comparison. It lies in a constrained area near a pass over the Kratke Range and is surrounded east and west by peaks to 2700m. It is further hemmed in by Tairora to the north and Avia to the south. These factors have restrained deforestation since 1957.

These data support our conclusion that Auyana was, and is, the last territory to be colonized and deforested by members of the Kainantu Sub-family. The GIS data make it clear that the deforestation and colonization of the upper altitude landscape in Auyana was ongoing in 1957 and has continued into the present. Auyana also provides a relatively discrete area (77 km^2 in 1957 and 105 km^2 in 2017) and a reasonably accurate population figure of 4710 in 1963. This figure is used to derive a 1957 population of 3850 based on growth rate estimates by Pataki-Schweizer (1980).

While it is important to establish that Auyana was the last area to be colonized and that the last phase of that colonization was in the recent past and after the adoption of sweet potato, which opened up the higher altitude perimeter in the basin above 1650m to settlement, it should be emphasized that the time of initial dispersal from the Awa parental group remains in question. The *terminus ad quem* date of 600 years as opposed to 400 BP is influenced by archaeological sequences at Aibura and Batari. The data from these sites are meager, to say the least. Furthermore, it is possible to conduct simulation trials for Vectors 1 and 3 that reach the Awa/Auyana border as late as 300 BP; from a technical point of view, a 400 BP or 500 BP date for the beginning of Auyana settlement is possible. Our use of the modeling approach is not to determine the precise date of arrival; however, there is evidence that the Auyana basin has been settled longer than 400 years, based on archaeological data derived from Cole's site survey (Figure 13). In addition, arrival dates later than 600 BP are less credible because they do not produce global and Auyana scale sets that exhibit conformity between trials with similar growth rates (see sub-section below titled "Conformity at Global and Auyana Scales").

Of the 11 sites below the 1650m contour that have no evidence of recency, four produced surface collections of sufficient size to allow inclusion for analysis by Watson and Cole (1977). This work also included a sequence of flaked stone assemblages from the 1964 excavation at Kafiavana (Watson and Cole 1977:129, Fig. 129). The Kafiavana lithics assemblages were stratified and dated. Watson applied a typology based on used edges to produce the seriation depicted in Figure 13. While Watson's classificatory approach has been misunderstood and criticized by Evans and Mountain (2005:366), this typology based on edges and the intersection of four modes and four attributes is the only typology applied to flaked stone lithics that has produced a chronostratigraphic framework in Papua New Guinea (Watson and Cole 1977:80.

Table 3. Showing increase in clearance of primary forest between 1957 and 2017, northeast Auyana, excepting Amaira.

Bounded complex	1957 Area square km	2017 Area square km	Increase square km	% Increase 1957–2017
Amaira	1.85	2.63	0.78	42.3
Avia	0.67	2.46	1.79	269.2
Waisempa	2.93	6.43	3.5	119.5
Nankona	11.52	17.34	5.71	49.6
Asempa	25.46	34.28	8.82	34.6
Totals	**42.43**	**63.14**	**20.6**	**48.6**

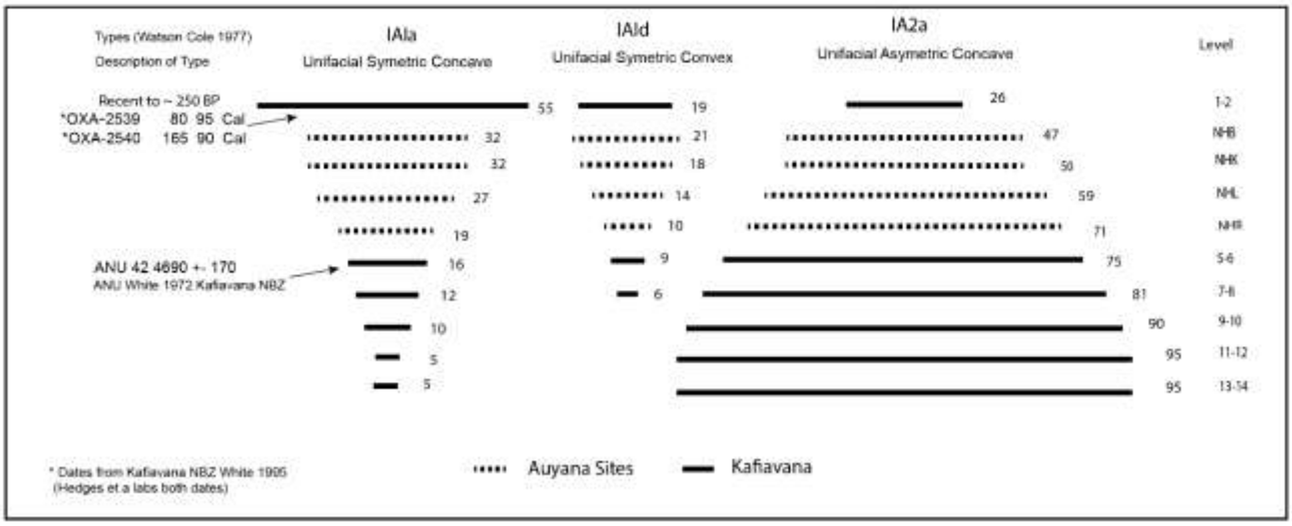

Figure 13. Seriation of three edge types known to be significant with respect to time (Watson and Cole 1977:129).

Watson applied this typology to surface collections from Cole's survey of the project area, including four sites in the Auyana/Fore border zone. Figure 13 adds this Auyana component (shown in dashed lines) to the previously published Kafiavana seriation diagram at the point where they fit, at a hiatus between levels dated between Cal 250±165 BP and approximately 4690±170 BP in which they belong toward the middle to lower end of that hiatus. While precise dating cannot be derived from seriations such as this, relatively speaking, this seriation argues persuasively for a date older than 400–500 BP and possibly older than the 600 BP for the *terminus ad quem* date. It also begs the question of when the earliest possible arrival date might be. That question will be addressed after our account of simulation trials for Vectors 1 and 3 below.

RESEARCH PROCEDURE

Our research procedure began with identification of potential anthropogenic changes reflected in archaeological and paleoecological sequences (Figure 9). A date (red dots) or date range (vertical blue bars) was then assigned to each change, using ranges based on information in site reports (White 1972; Watson and Cole 1977; Cole 1996; Haberle 1996). Initially, a set of six vectors (Figures 9 and 10) were projected to connect all possible sequences of changes in site assemblages and features. Vectors 2, 4, and 6 were eliminated because they represent scenarios in which taro and yam would not be known by Awa speakers prior to contact (Figure 10). This contradicts the historically recorded fact that taro and yam *were* cultivated by Awa speakers prior to western contact. The trials were then conducted with attention to finding best-fit simulation models corresponding to the remaining vectors, V1, V3, and V5.

The Simulations: Reading Simulation Trial Results

Simulation algorithms are coded in Excel spreadsheets. The population algorithm is a register that accumulates annual increases in population based on growth rate. Pre-ipomoean growth rate is an operator-controlled variable. It is expressed as a positive number and ranges between 0.000001 and 0.03 (in this notation a growth rate of, e.g., 1.25% will appear as 0.0125 throughout). Growth rates are entered and read out as positive numbers that represent averages over specified time intervals (500, 100, etc., years), and it is assumed that those growth rates average negative and positive fluctuations and should not be taken to imply smooth or steady growth rates at smaller scales. With each iteration (year), a new accumulated population is used to calculate the area of primary forest removed. This value is also accumulated. The calculation for primary forest cleared is as follows:

PFC = P × PU% × APU × FC%,

where PFC = primary forest cleared in m^2 per annum; P = population; PU% = production units as a percentage of the population (held as a constant of 59.7%); APU = area of primary forest cleared per PU in m^2; FC% = percent of total garden area taken from primary forest (this is an operator-controlled variable).

Trials are reported in tables that record operator inputs and computed outputs (see example in Table 4). Date and time intervals are indicated in the extreme left column, followed by growth rates for each interval. The garden area cleared per PU is 989 m^2 for the pre-ipomoean period and 1023 m^2 for the post-ipomoean period, followed by a column listing the primary forest clearance rate for each interval.

Table 4. A typical trial result for Vector 1.*

INPUTS					Outputs				
Date	Era	Growth Rate	SqKm Per PU	Clearing Rate	Popu-lation	Total Cleared	Density	Constraint Population	Constraint Grassland
3500	BP	0.00057	989	0.35	325	0.1			
3000	BP	0.00057	989	0.2	432	38.8	11.1		
2500	BP	0.00057	989	0.2	575	68.4	8.4		
2000	BP	0.00057	989	0.2	765	107.6	7.1		
1500	BP	0.00057	989	0.2	1,018	159.8	6.4		
1000	BP	0.00057	989	0.2	1,354	229.3	5.9		
600	BP	0.00057	989	0.128	1,701	301.0	5.7	2,908	303
400	BP	0.00057	989	0.128	1,906	328.1	5.8		
300	BP	0.00057	989	0.128	2,018	342.9	5.9		
200	BP	0.002166	**1023**	0.128	2,136	358.6	6.0		
100	BP	0.0125	1023	0.128	2,653	377.3	7.0		
0	BP	0.015	1023	0.128	9,190	418.6	22.0		
1963	CE	0.022	1023	0.128	11,153	428.9	26.0	11,155	
1972	CE	0.025	1023	0.128	13,566	437.7	31.0		
2000	CE	0.0275	1023	0.128	27,085	480.9	56.3		
2017	CE	0.03	1023	0.128	42,956	527.2	81.5		527

**Note that the density figure for the first time interval is omitted. This is because the figure is misleadingly inflated in all trials. Were it included in this trial, for example, it would be 3500 persons per km^2. This distortion is caused by the lag in accumulated cleared area at the outset of the migration. This distortion is evened out in the second and third intervals.*

The outputs are on the right side of the table, starting with accumulated population, followed by the accumulated primary forest cleared (in km^2), and the mean density ratio for that interval. The density value represents the population divided by the amount of cleared area. Cleared area includes long and short grassland, gardens, fallow land, and secondary growth. In other words, all land that is not covered by primary forest excluding major rock outcrops, landslides, and other natural clearings. Important constraints are entered on the right and are color-coded to assist the reader in comparing the computed totals with the constraint. The growth rate cell at 200 BP is highlighted in orange to emphasize that the value in that cell is especially important. The 200 BP growth rate cell contains a special value. It is called a "hinge value" (see below) since it mediates the pre- and post-ipomoean population growth rates across this important change in subsistence. The 250 BP date is the focal date estimated for sweet potato to have been available in South Tairora and Auyana, noting that we estimate it was later for the smaller population of Awa speakers, the ancestors of the 1971–72 Awa population (approximately 10% of the total estimated population of 11,155 in the project area in 1972).

Conformity at Global and Auyana Scales

Simulations pertaining to each vector are conducted at two scales: namely, "Global" (meaning the entire project area—Aibura, Batari, South Tairora, Awa, Auyana) and the smaller "Auyana" scale. Trial tables will sometimes be presented as sets that include both scales. In determining the "best fit" trials, greater credibility is placed on sets that use similar pre-ipomoean growth rate sequences and display conformity such that the trials with similar growth rates meet constraints at both scales. In these sets, the hinge growth rate value at 200 BP may differ since Global and Auyana trials model two different scenarios, but even then, the hinge values must conform to prescribed limits which are explained below. Except for the hinge value at 200 BP, all post-ipomoean growth rates are identical since they are either observed values or derived through interpolation from values summarized from patrol reports or ethnographic sources. In all simulations, regardless of scale, the number of initial founders is a constant of 325 persons.

Hinge Cell Values

The term *hinge cell* was adopted to refer to the cell in the growth rate column in the 200 BP row of a trial's table. It contains the growth rate value that mediates the mean pre-ipomoean growth rate for a given trial with the post-ipomoean growth rate (Table 5).

Two rules governing hinge cell value were adopted and are explained as follows:

1. The hinge cell value must be higher than the value of the 300 BP growth rate cell. This is consistent with the assumption that the impact of sweet potato on the economy of the project area was essentially positive, leading to a significant increase in the population growth rate.
2. The hinge cell value must be less than 0.01. This ensures that the increase in growth rate in the 200 BP interval is not larger than the subsequent increase in growth in the 100 BP interval. In other words, to be consistent with the assumption that sweet potato increased growth rate, there should be no setback in the running average over 100-year intervals in the early phases of its adoption. There might be brief setbacks, but given the many advantages of sweet potato, these setbacks should be brief and increase as the new crop is accepted and as populations adapt to and integrate the new crop into their subsistence economy. Even in Irakia Awa where the acceptance has been slow, the 1971–72 population growth rate of 1.25% was well above our largest pre-ipomoean estimates (Boyd 1975:82).

These rules are applied to ascertain the minimum and maximum values for pre-ipomoean growth rates for Vectors 1, 3, and 5 and will be further elucidated in the trials for these vectors that follow.

Table 5. Sources for pre- and post-ipomoean values used in all trials presented in this report.

Date	Era	Value	Data Type	Sources
300	BP	0.00057	pre-ipomoean mean	Operator: defines a unique trial
200	BP	0.00086	Hinge cell	Determined by trial and error
100	BP	0.0125	post-ipomoean fixed	Interpolated Boyd 1975
0	BP	0.015	post-ipomoean fixed	Interpolated Boyd 1975 Pataki-Schweizer 1980
1963	CE	0.0122	post-ipomoean fixed	Boyd 1975 Pataki-Schweizer 1980
1972	CE	0.025	post-ipomoean fixed	Boyd 1975 Pataki-Schweizer 1980
2017	CE	0.03	post-ipomoean fixed	Sherman *et al*. 2008

Vector 1. Global Simulation Trials: Modeling a Population Migration Beginning at the Headwaters of the Lamari River in 3500 BP

The lowest growth rate series for Vector 1 at the global scale is represented in Table 6. As the value in the hinge cell reaches the upper limit of 0.01, the pre-ipomoean population growth rate reaches 0.00033. At this growth rate, a mean primary forest clearance rate of 35% is required to traverse the distance to the Awa/Auyana border zone by 600 BP, meeting and slightly exceeding the 303 km^2 constraint for area cleared while falling short of the 1509 constraint for population. This results in low density figures and indicates that the lowest allowable growth rate is significantly higher than 0.00033. In Table 7 a growth rate of 0.00053 produces an average over the four lowest densities of 4.9 with a grassland area of 305.5 km^2 and is taken as the corrected lowest growth rate for Vector 1 at the Global scale (margin of error <2.0%).

The highest possible growth rate series for Global scale of Vector 1 is given in Table 8.

Table 6. Lowest possible growth rate trial table for Vector 1 (Global scale), disregarding the necessity for density to be greater or equal to 5.

Date	Era	Growth Rate	SqKm Per PU	Clearing Rate	Popu-lation	Total Cleared	Density	Constraint Population	Constraint Grassland
3500	BP	0.00033	989	0.35	325	0.1			
3000	BP	0.00033	989	0.35	384	36.6	10.5		
2500	BP	0.00033	989	0.35	454	79.7	5.7		
2000	BP	0.00033	989	0.35	537	130.7	4.1		
1500	BP	0.00033	989	0.35	635	191.0	3.3		
1000	BP	0.00033	989	0.35	750	262.3	2.9		
600	BP	0.00033	989	0.35	858	328.6	2.6	1509	303
400	BP	0.00033	989	0.113	917	365.0	2.5		
300	BP	0.00033	1023	0.113	948	371.3	2.6		
200	BP	0.01	1023	0.113	980	377.9	2.6		
100	BP	0.0125	1023	0.113	2,653	389.5	6.8		
0	BP	0.015	1023	0.113	9,192	426.0	21.6		
1963	CE	0.022	1023	0.113	11,155	435.2	25.6	11155	
1972	CE	0.025	1023	0.113	13,569	442.9	30.6		
2000	CE	0.0275	1023	0.113	27,091	481.1	56.3		
2017	CE	0.03	1023	0.113	42,966	527.0	82.3		527

Table 7. This table corrects the trial in Table 6 by applying the density rule.*

Date	Era	Growth Rate	SqKm Per PU	Clearing Rate	Popu-lation	Total Cleared	Density	Constraint Population	Constraint Grassland
3500	BP	0.00053	989	0.2315	325	0.2			
3000	BP	0.00053	989	0.2315	424	25.4	16.7		
2500	BP	0.00053	989	0.2315	552	58.6	9.4		
2000	BP	0.00053	989	0.2315	720	101.7	7.1		
1500	BP	0.00053	989	0.2315	938	157.9	5.9		
1000	BP	0.00053	989	0.2315	1,222	231.2	5.3		
600	BP	0.00053	989	0.2315	1,510	305.5	4.9	1,509.0	303
400	BP	0.00053	989	0.1177	1,679	348.9	4.8		
300	BP	0.00053	1023	0.1177	1,770	360.8	4.9		
200	BP	0.00353	1023	0.1177	1,866	373.9	5.0		
100	BP	0.0125	1023	0.1177	2,654	390.0	6.8		
0	BP	0.015	1023	0.1177	9,193	428.0	21.5		
1963	CE	0.022	1023	0.1177	11,156	437.5	25.5	11,155.0	
1972	CE	0.025	1023	0.1177	13,570	445.6	30.5		
2000	CE	0.0275	1023	0.113	27,093	485.3	55.8		
2017	CE	0.03	1023	0.113	42,969	526.1	81.7		527

**For this purpose, we average the four lower density values; in this case, the result is 4.9, which is within 2% of 5 and thus within the margin for error used throughout.*

Table 8. This table represents the highest possible pre-ipomoean growth rate for Vector 1 at 0.00062 as indicated by the hinge cell value at 200 BP, which is equal to that at the 300 BP value.*

Date	Era	Growth Rate	SqKm Per PU	Clearing Rate	Popu-lation	Total Cleared	Density	Constraint Population	Constraint Grassland
3500	BP	0.00062	989	0.2	325	0			
3000	BP	0.00062	989	0.2	443	22	19.7		
2500	BP	0.00062	989	0.2	603	53	11.4		
2000	BP	0.00062	989	0.2	821	95	8.7		
1500	BP	0.00062	989	0.2	1,118	151	7.4		
1000	BP	0.00062	989	0.2	1,523	229	6.7		
600	BP	0.00062	989	0.1177	1,949	310	6.3	1,509	303
400	BP	0.00062	989	0.1177	2,205	339	6.5		
300	BP	0.00062	1023	0.1177	2,346	355	6.6		
200	BP	0.00062	1023	0.1177	2,495	372	6.7		
100	BP	0.0125	1023	0.1177	2,654	391	6.8		
0	BP	0.015	1023	0.1177	9,193	429	21.5		
1963	CE	0.022	1023	0.1177	11,156	438	25.5	11,155	
1972	CE	0.025	1023	0.1177	13,570	446	30.4		
2000	CE	0.0275	1023	0.113	27,094	486	55.8		
2017	CE	0.03	1023	0.113	42,970	527	81.6		527

**A higher growth rate would force the hinge cell value to go lower than the 300 BP value to stay within the 1962 population constraint. This is not permitted. The density is optimal in this trial.*

Vector 3. Global Simulation Trials: Modeling a Migration Beginning at the Headwaters of the Lamari River in 2000 BP

A similar set of trials was used to ascertain the lower and upper growth rate values for Vector 3. The Vector 3 range was found to be 0.000694 to 0.00115 (Tables 9, 10, and 11). The density test in Table 9 for the lower end of this range did not meet the required population density value of 5.0/km^2. It was therefore replaced by the trial in Table 10 with a growth rate of 0.00115.

Table 9. This trial determines the lowest possible growth rate, but the resulting density is too far below the required lower limit of 5/km^2.

Date	Era	Growth Rate	SqKm Per PU	Clearing Rate	Popu-lation	Total Cleared	Density	Constraint Population	Constraint Grassland
2000	BP	0.0006938	989	0.674	325	0.1			
1500	BP	0.0006938	989	0.674	460	77.4	5.9		
1000	BP	0.0006938	989	0.674	651	186.7	3.5		
600	BP	0.0006938	989	0.674	796	304.6	2.6	1,509	303
400	BP	0.0006938	989	0.114	853	371.0	2.3		
300	BP	0.0006938	989	0.114	915	376.9	2.4		
200	BP	**0.01**	989	0.114	980	383.3	2.6		
100	BP	0.0125	1023	0.114	2,653	394.7	6.7		
0	BP	0.015	1023	0.114	9,192	431.5	21.3		
1963	CE	0.022	1023	0.114	11,156	436.2	25.6	11,155	
1972	CE	0.025	1023	0.114	13,570	448.5	30.3		
2000	CE	0.025	1023	0.114	27,092	487.0	55.6		
2017	CE	0.03	1023	0.114	41,225	527.3	78.2		527

Table 10. This trial corrects the Vector 3 trial in Table 9 (lowest possible growth rate) for density by raising the growth rate from 0.000694 to 0.00115.*

Date	Era	Growth Rate	SqKm Per PU	Clearing Rate	Popu-lation	Total Cleared	Density	Constraint Population	Constraint Grassland
2000	BP	0.00115	989	0.46	325	0.1			
1500	BP	0.00115	989	0.46	578	59.7	9.7		
1000	BP	0.00115	989	0.46	1,028	165.7	6.2		
600	BP	0.00115	989	0.46	1,433	304.5	4.7	1,509	303
400	BP	0.00115	989	0.088	1,804	391.5	4.6		
300	BP	0.00115	989	0.088	2,024	401.4	5.0		
200	BP	0.00156	989	0.088	2,270	412.6	5.5		
100	BP	0.0125	1023	0.088	2,653	425.3	6.2		
0	BP	0.015	1023	0.088	9,193	453.7	20.3		
1963	CE	0.022	1023	0.088	11,156	457.4	24.4	11,155	
1972	CE	0.025	1023	0.088	13,570	466.9	29.1		
2000	CE	0.025	1023	0.088	27,093	496.6	54.6		
2017	CE	0.03	1023	0.088	41,225	527.7	78.1		527

**In this case, the resulting density average over the lowest four values is 5.1/km^2.*

Table 11. This trial determines the highest possible growth rate for Vector 3.*

Date	Era	Growth Rate	SqKm Per PU	Clearing Rate	Population	Total Cleared	Density	Constraint Population	Constraint Grassland
2000	BP	0.00117	989	0.448	325	0.1			
1500	BP	0.00117	989	0.448	585	58.5	10.0		
1000	BP	0.00117	989	0.448	1,052	163.6	6.4		
600	BP	0.00117	989	0.448	1,476	302.5	4.9	1,509	303
400	BP	0.00117	989	0.088	1,867	390.1	4.8		
300	BP	0.00117	989	0.088	2,099	400.3	5.2		
200	BP	0.00117	989	0.088	2,360	411.9	5.7		
100	BP	0.0125	1023	0.088	2,654	424.9	6.2		
0	BP	0.015	1023	0.088	9,194	453.3	20.3		
1963	CE	0.022	1023	0.088	11,158	457.0	24.4	11,155	
1972	CE	0.025	1023	0.088	13,572	466.5	29.1		
2000	CE	0.025	1023	0.088	27,097	496.2	54.6		
2017	CE	0.03	1023	0.088	41,232	527.3	78.2		527

**The result of the trials in Tables 10 and 11 is a very small growth rate range for Vector 3.*

Disqualification of Vector 5 as an Initial Dispersal Vector

The trial in Table 12 is an example of failure to meet constraints. The growth rate is as high as it can be, yet the population at 600 BP is so low that even with the primary forest clearing rate of 100%, only 126 km^2 are removed in the 400 years between the start of the dispersal and 600 BP. This places the frontier less than half the distance to the Awa/Auyana border zone. While this disqualifies Vector 5 as an initial dispersal vector, the changes in Aibura and Batari assemblages that Vector 5 represents could represent a secondary dispersal, perhaps over land already cleared by forerunners, namely one or both of the populations comprising dispersals modeled by in Vector 1 and/or Vector 3. It also might be called upon to explain the present distribution of languages. This will be discussed in the conclusion.

Auyana (Only) Scale, Determining High and Low Population Growth Rate Values for Vectors 1 and 3

Trials at the Auyana scale are conducted to determine the full range of pre-ipomoean growth rate values for trials at this smaller scale. These trials are reported in Tables 13a and 13b (below). The constraints are adjusted slightly because the area measurements at this scale are determined from 1957 aerial photographs. The population constraint is calculated for the same date using interpolation from the 1962 figure of 4210 and the 2.2% growth rate data estimate by Pataki-Schweizer (1980).

The trials in Table 13a and 13b encompass and confirm the full range of global scale Vector 1 pre-ipomoean growth rates (0.00053 to 0.00062) and meet all constraints. The trials in Table 13a and 13b also encompass and confirm the global scale trials for Vector 3 (0.00115 to 0.00117). The density values for the Auyana scale trials are well above the limit of 5. This is not surprising since we have a new dispersal of 325 persons into a primary forest.

Table 12. Table for a trial of Vector 5 showing that Vector 5 does not meet the essential area constraint at the 600 BP cell for primary total forest cleared and is therefore disqualified as a model for an initial colonizing migration.

Date	Era	Growth Rate	SqKm Per PU	Clearing Rate	Population	Total Cleared	Density	Constraint Population	Constraint Grassland
1000	BP	0.0023	989	1	325	0.2			
600	BP	0.0023	989	0.244	827	126.7	6.5	2,908	303
400	BP	0.0023	989	0.244	1,319	157.1	8.4		
300	BP	0.0023	1023	0.244	1,665	178.5	9.3		
200	BP	0.0023	1023	0.244	2,102	206.4	10.2		
100	BP	0.0125	1023	0.244	2,654	241.6	11.0		
0	BP	0.015	1023	0.244	9,194	320.4	28.7		
1963	CE	0.022	1023	0.244	11,157	340.2	32.8	11,155	
1972	CE	0.025	1023	0.244	13,572	356.9	38.0		
2000	CE	0.0275	1023	0.244	27,097	439.4	61.7		
2017	CE	0.03	1023	0.244	42,975	527.6	81.4		527

Table 13a. Lowest population growth rate for Auyana scale trials is 0.0003 (hinge cell value is at upper allowable limit of 0.01).

Date	Era	Growth Rate	SqKm Per PU	Clearing Rate	Population	Total Cleared	Density	Constraint Population	Constraint Grassland
600	BP	0.0003	989	0.315	325	0.1			
400	BP	0.0003	989	0.315	347	12.5	25.9		
300	BP	0.0003	989	0.315	358	19.1	18.2		
200	BP	0.01	989	0.315	370	25.8	13.9		
100	BP	0.0125	1023	0.315	1,001	37.7	9.8		
0	BP	0.015	1023	0.095	3,470	75.6	13.2		
1957	CE	0.022	1023	0.095	3,851	77.1	45.0	3,850	77
1972	CE	0.025	1023	0.095	5,122	80.9	47.6		
2000	CE	0.025	1023	0.095	10,228	93.1	55.0		
2017	CE	0.03	1023	0.095	15,563	105.7	96.7		105

Table 13b. Highest possible growth rate for Auyana scale trials is 0.0022 with hinge cell value equal to the preceding 300 BP value.

Date	Era	Growth Rate	SqKm Per PU	Clearing Rate	Population	Total Cleared	Density	Constraint Population	Constraint Grassland
600	BP	0.0022	989	0.255	325	0.0	0.0		
400	BP	0.0022	989	0.255	510	12.4	41.1		
300	BP	0.0022	989	0.255	638	21.0	30.4		
200	BP	0.0022	989	0.255	799	31.8	25.2		
100	BP	0.0125	1023	0.255	1,001	45.3	22.1		
0	BP	0.015	1023	0.093	3,469	76.0	45.6		
1957	CE	0.022	1023	0.093	3,850	77.5	49.7	3,850	77
1972	CE	0.025	1023	0.093	5,121	81.2	63.0		
2000	CE	0.025	1023	0.093	10,225	93.1	109.8		
2017	CE	0.03	1023	0.093	15,559	105.5	147.5		105

Earliest Time of Arrival at the Auyana 1650m Contour

It is possible to use simulations to estimate the earliest possible arrival date. To do this, it is necessary to consider the situation in which colonists arrive at the Awa/Auyana border zone well before the introduction of sweet potato. We have assumed that without sweet potato, colonists would garden land at or below the 1650m contour. Assuming this to be the case, the population dispersal would press forward into Auyana and become arrested at the 1650m contour until the arrival of sweet potato. There are 47.4 km^2 at or below that level in Auyana and 303.2 km^2 below the 1650m contour in the rest of the project area (before rounding). We therefore increase the constraint for forest cleared to 351 m^2. The question therefore becomes how quickly a founding population of 325 persons can clear 351 km^2 of primary forest.

Since we want to determine the earliest possible date of arrival at the Auyana 1650 m contour we use the *maximum* growth rate from our best-of-fit Vector 1 and 3 models, which is 0.00117. The result of this computation is Table 14.

Table 14. Modeling Vector 3 earliest arrival date for Vector 3 at the 1650 m contour.

Date Era	Growth Rate	SqKm Per PU	Clearing Rate	Popu-Lation	Total Cleared	Density	Constraint Population	Constraint Grassland
2000 BP	0.00117	989	100	325	0.02		0.02	
1500 BP	0.00117	989	100	585	130.6	4.5	130.6	
1000 BP	0.00117	989	100	1,052	364.9	2.9		351

This would indicate that an earliest date of arrival at the Auyana 1650m contour for Vector 3 is 1000 BP. However, in this trial, it is necessary to take 100% of agricultural land from primary forest to meet the 351 km^2 constraint. This is an extreme rate and is not considered feasible over a 1000-year period. An *ideal* rate is 50% (Tok Pisin: *hap-hap*, "half-half"), according to Robbins's Auyana informant. In addition, the population density of 2.9/km^2 in the simulation in Table 14 is too low. This trial was therefore rejected.

A credible estimate for the arrival date for Vector 3 as calculated in Table 15 is 700 BP. The primary forest clearance rate in this trial is 60% and its density is closer to 5.0/km^2 (using a mean of the four highest values, it is 4.9). While the clearance rate of 60% is slightly higher than the rate Robbin's survey suggests, in view of the limited sample for his estimate of 50%, local variability, and the lack of data from other locations, the 50% is not considered to be a constraint and is not held to the <2% margin of error.

Table 15. Modeling Vector 3 earliest arrival date at the Auyana 1650 m contour.

Date Era	Growth Rate	SqKm Per PU	Clearing Rate	Popu-lation	Total Cleared	Density	Constraint Population	Constraint Grassland
2000 BP	0.001173	989	0.6	325	0.1			
1500 BP	0.001173	989	0.6	585	84.9	6.9		
1000 BP	0.001173	989	0.6	1.052	237.4	4.3		
800 BP	0.001173	989	0.6	1,330	328.3	4.1		
700 BP	0.001173	989	0.6	1,476	352.9	4.18		351

In the case of Vector 1, since the migration starts at 3500 BP it could take much longer and the arrival date at the Auyana 1650m contour would be in the range of 2500 BP to 600 BP if we apply the same parameters. However, there is much more latitude for this vector. The growth rate and the primary forest clearance rate could be very low in which case the migration would move through Batari well before the smallest change in that site's archaeological deposit at 3000 BP. This can be corrected by limiting the earliest arrival date at the Auyana 1650m contour to 2000 BP, in which case the transit from Aibura to the Auyana 1650m contour would take 1500 years, as indicated in Table 16. In this scenario, density is well above 5.0/km^2, and the forest clearance rate is close to the ideal according to Robbins's informant.

Table 16. Modeling Vector 1 earliest arrival date at the Auyana 1650m contour.

Date Era	Growth Rate	SqKm Per PU	Clearing Rate	Population	Total Cleared	Density	Constraint Population	Constraint Grassland
3500 BP	0.00117	989	0.45	325	0.1			
3000 BP	0.00117	989	0.45	583	58.8	9.9		
2500 BP	0.00117	989	0.45	1,049	164.1	6.4		
2000 BP	0.00117	989	0.45	1,902	353.5	5.4		351

DISCUSSION

The models depicted in Tables 6 through 16 simulate transgressive change across time and space. In doing so, they average volatile scenarios of rising and falling population growth and land-use practices, including primary forest use-ratios from 0% to 60%. This range is based on ethnographic sources and GIS analysis of legacy aerial photography (Boyd 1975; Sorenson 1976; Robbins 1982; Sillitoe 1996; Roberts 2017). For example, Robbins (1982:56) surveyed 171 gardens in Auyana in 1962 and found 74 to be cut from primary forest or significantly aged regrowth forest. He also states, "The optimal condition for gardening would be to have one or more plots recently made from forest and one or more plots made from grassland or secondary growth". His field work was carried out near and in central Auyana, an area where moderate deforestation has taken place over the past 50 years (Table 3). We estimate that a 60% average for the primary clearance ratio would be at the high end of the range for Auyana in recent times; likewise for South Tairora, which has also cut aggressively in the last 50 years. Awa, on the other hand, has cut little, less than 5% annually since 1943, as determined by our GIS measurements based on georeferenced aerial photographs. In this regard, there is justification for higher primary forest clearance rates at the outset of dispersal event, since it takes an estimated average of 15 years to clear sufficient primary forest to initiate a 10- to 20-year system of fallow recycling. In addition, there is ethnographic evidence that intragroup friction and intergroup enmity were frequent motivations for fission and population dispersal (Sorenson 1976; Robbins 1982; Watson 1983). It is reasonable to assume that once a pioneering group became independent of its parental group, it would begin a process of differentiation and identity formation that would require further distancing for safety from attack by the parental group, its allies, and/or its enemies.

Simulation trials were conducted to create models that approximate constraints and minimize unjustified variations in operator-controlled variables to avoid forcing results. Variations that weaken the credibility of the model were discarded unless there was evidence to the contrary. The trial-and-error process of model making reifies the relationship between demography and landscape change and demonstrates the inaccuracy if not irrelevance of terms such as *revolutionary*, *explosive*, *moderate*, *intermittent*, and *steady* when applied to the realities of population growth and its entailments. It offers a promising way to achieve progress in archeological research by using operations that are structured, quantified, and tested against numerical constraints, dated changes, and stratified sequences. Had anthropologists utilized such ideas earlier, decades of argument could have been avoided, although given concerns about Malthusian determinism in that era, it might not have been a realistic alternative.

Because archaeological and paleoecological evidence is meager and there are few stratified sequences from the project area, our models are useful approaches to the problem of synthesis and hypothesis formation. They are also useful for design of further research by suggesting efficient designs for future survey and excavation projects, for example, survey of habitable ridges, especially those near the 1500m to 1650m contours on an east-west transect through the Lamari watershed. Additional palaeoecological research in the lower Lamari Valley and the Auyana basin would also contribute significantly to our understanding and future modeling efforts. In addition, it is possible to use this kind of modeling to construct simulations that include temporal scales of change for the project area. Our modeling limits the initial dispersal of semi-sedentary populations to a range of approximately ~3500 to ~2000 BP with reasonable certainty. This scale is also consistent with linguistic evidence, suggesting that the dispersal sequence is complex and consisted of at least two migratory waves. The prehistory of the present language picture is elaborated with more detail in the conclusions that follow. Figure 14 summarizes the results of over 200 simulation trials undertaken to compute best-fit models for dispersal events modeled by Vectors 1 and 3.

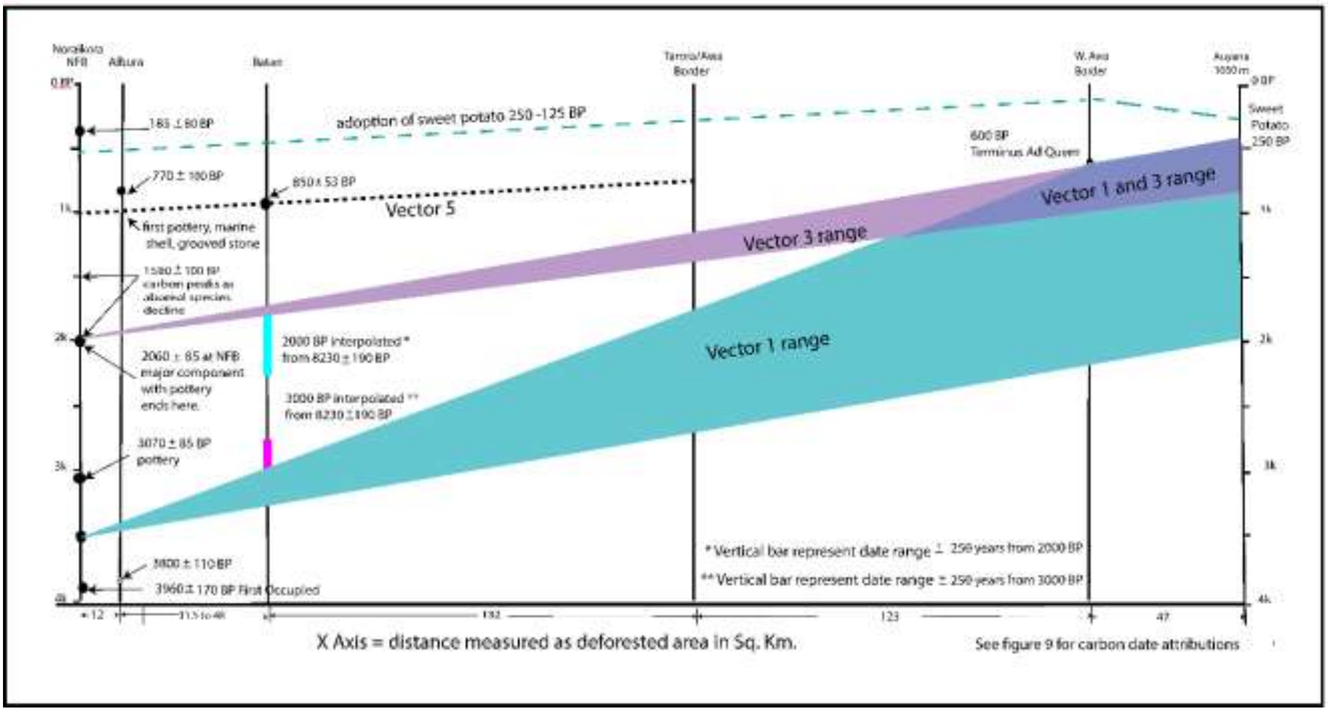

Figure 14. Summarizing the range of vectors as to date of arrival at the western extremity of the project area in the Auyana uplands in 2017, as determined by simulation trials. Source: The authors.

Above all, simulation modeling is not a substitution for analytic techniques in situations where adequate C_{14} datasets are available. The present study synthesizes data from many disciplines (paleoenvironmental, archaeological, demography, GIS, ethnohistory, and linguistics) in compensation for the absence of adequate and reliable C_{14} sequences. Were there a sufficiency of C_{14} datasets from these early excavations, simulation modeling would be additionally useful to the task of interpreting the relationship of these larger datasets to human activities (Attenbrow and Hiscock 2015:34). It is likely, given advances in carbon and luminescence dating methods, that collections from early excavations in the study area contain an adequate number of samples to make that research possible. This combined with further paleoenvironmental sampling in the Lamari Valley and Auyana basin would ultimately test this procedure and its outcomes and would greatly enhance the research.

CONCLUSION

Several deductions follow from these considerations:

1. The processual changes represented in these simulations include language and its diversification. Fission and population dispersal by pre-ipomoean colonizing groups produced linguistic diversification from two proto-linguistic groups, termed Tagauwa and Tairora, which generated three languages in the Lamari River and Auyana portion of the study area. This diversification is consistent with an analysis of linguistic distance by Howard McKaughan and 17 collaborators of the Summer Institute of Linguistics, who concluded that the Awa and Auyana languages are more similar to Gadsup than to Tairora (McKaughan 1973); Figure 15 depicts this probable differentiation. This conclusion requires two diffusion events. The first is depicted in Figure 15, subsets A and B, in which Gauwa and later Tairora proto-language speakers colonize the Lamari Valley. The second dispersal is shown in subsets C and D, with ancestral Tairora speakers following Gauwa speakers through the lower Lamari River valley. This movement isolated the Gauwa group from ancestral Gadsup speakers as dispersal proceeded to the south and west, where language and ethnic identity eventually emerged as the Awa and Auyana ethnolinguistic groups, i.e., cultures. Our simulations provide overlapping time frames for combinations of Vectors 1 and 3 and the partial dispersal vector (Vector 5). These scenarios can accommodate the ethnolinguistic distribution described by McKaughan and represented in Figure 15.
2. Our simulation models suggest that after an initial period of 15 to 30 years, the initiators of these fission and dispersal events could successfully sustain themselves for protracted periods of time with relatively little use of primary forest. This also suggests that the present grassland expanse in this and possibly other highland landscapes may not be primarily due to horticultural necessity; factors such as population density, enmity and warfare, long-term soil exhaustion exacerbated by burning to collect mammals, or other larger-scale anthropogenic and ecological processes are also possible causes.
3. In terms of present tense, these simulations dramatically reflect the effects of the introduction of sweet potato: its high productivity, shorter growth period, and the resulting increased population density and land use, including forest above 1650m. This set of simulations indicates that post-ipomoean deforestation was the result of increased population growth and higher population densities. These pre-contact changes promoted greater contact, enmity and violence, and compensatory exchange systems, which in turn increased demand for pigs, sweet potato as the preferred fodder for pigs, and space; see Supplement 3.

4 Finally, the effects of post-contact changes also accelerated growth rates by ending tribal warfare and introducing steel tools such as axes and spades, newer foods, health services, and the gradual inclusions of newer political structures such as community governments, which resulted in less violence and overall greater stability after the immediate post-WWII contact period.

In summary, our research adds newer sequences and dimensions for the archaeology and history of the Eastern Highlands and Papua New Guinea. We intend to further develop these processes of time, scale, archaeology, and human ecology to produce more meaningful statements about pre- and post-contact periods, as well as a better synthesis of archaeology, environment, and human agency.

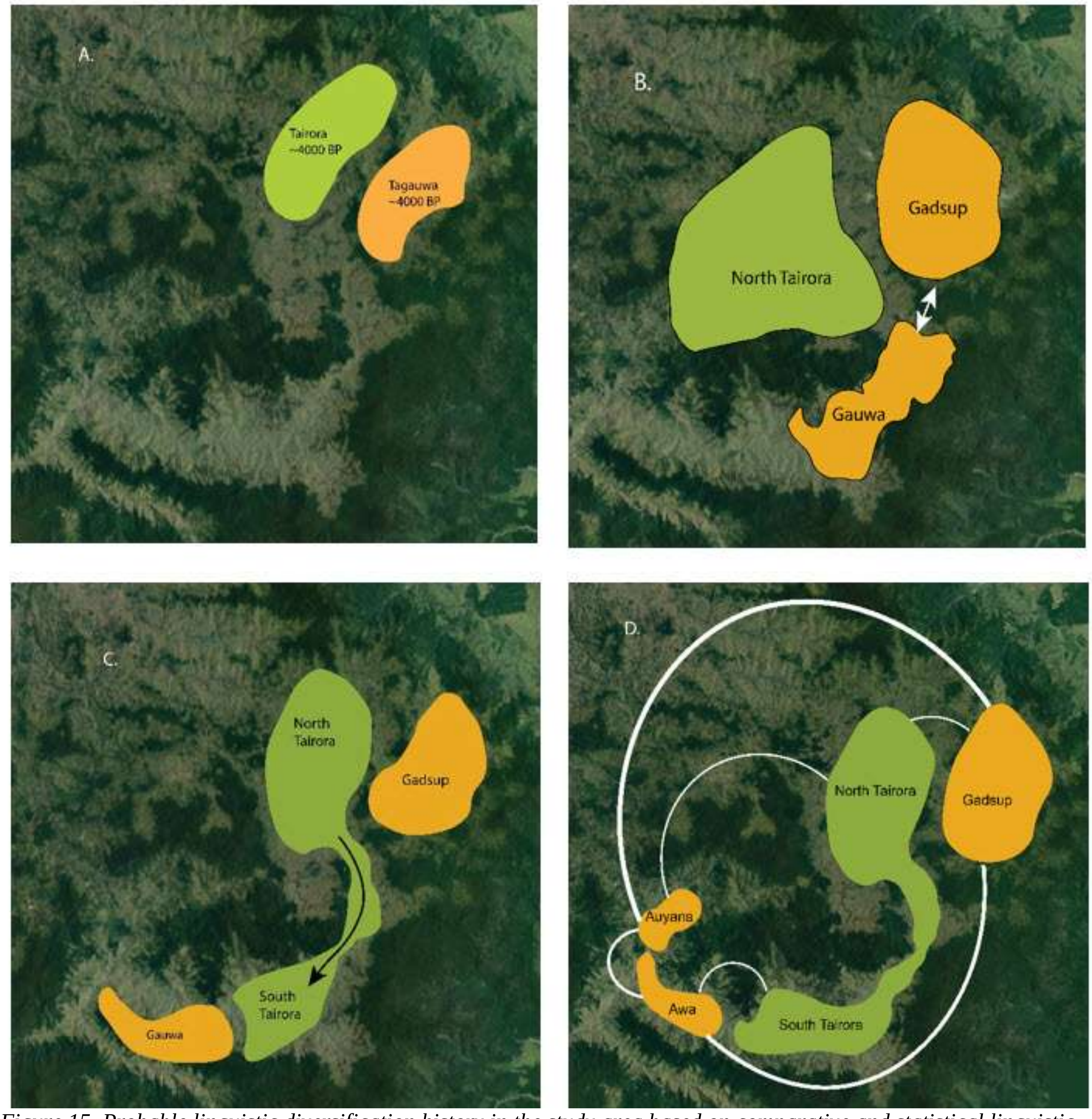

Figure 15. Probable linguistic diversification history in the study area based on comparative and statistical linguistic analysis, with greater diversity shown by thinner white lines (McKaughan 1973). Illustration: David Cole.

ACKNOWLEDGMENTS

We are grateful to Peter Lape and Laura Phillips of the Burke Museum, University of Washington, Simon Haberle of the Australian National University, J. Peter White of the University of Sydney, Christina Friedle, Eric Roberts and colleagues in the Department of Geography and GIS program at Portland Community College, David Boyd, Terry Hays, Geoff Hayes, and Andrew Pawley. We also thank Rosemary Cole, Tute of BenaBena, Taku of SinaSina, Tabe, Lebi, Pi'a'o, and Myna of Abi'era, Puano of Aba'ora and Sasapimpa of Asempa, who were diligent in the field, and Keith Weigel M.D. for his excellent assistance in the field and laboratory. The comments of two anonymous referees are also gratefully acknowledged.

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