Supplementary Material

# Supplementary Data

**Supplement to 3.1: On the Age of the Terraces**

 Scholars are divided on the age of the Ifugao terraces and the society they support. Traditionally, early scholars such as Franklin Barton and H. Otley Beyer, both of whom are seminal figures in the English-speaking historiography of the Ifugao region, argued the terraces emerged over thousands of years (Barton 1922; Beyer 1953). Neither, however, offered evidence for the terraces’ “long history.” Instead, the notion that the terraces are ancient comes from the presumed limitations of pre-modern societies engaged in “megalithic” construction (Beyer 1953).

 Although the long-history theory remains widely accepted among the broader public (UNESCO 1995), most scholarship since the 1960s has argued the terraces were recently constructed or expanded, partially in response to Spanish conquests in the lowlands. The first proponent of this theory was ethnographer Felix Keesing whose *The* *Ethnohistory of Northern Luzon* was published posthumously in a semi-finished state by his son in 1962. Keesing noted the arrival of the Spanish prompted precipitous depopulation of the Upper Cagayan Valley, including along the Magat River that marks the southern border of modern Ifugao Province. These peoples, who were rice cultivators (Amano et al 2020), were thought to have fled upland, moving with the rivers into the mountains. Keesing’s discussion of this depopulation ends with a tantalizing prospect: “The greatest problem…is the apparent dissipation around the beginnings of the seventeenth century of the extensive population reported in the Magat valley areas. The question must arise whether the wet-terracing Ifugao of later times trace back to this population” (1962, p. 300). Among the implications of Keesing’s new hypothesis was that the terraces were not ancient, but in fact recent, a response to Spanish colonialism and lowland refugees.

 Another mid-century scholar to address the terraces’ age was Francis Lambrecht, a missionary and scholar of Luzon’s highlands who reportedly found Keesing’s evidence unconvincing but his theory worth further exploration (Maher 1973). To assess the age of the terraces, Lambrecht studied Ifugao genealogies in Mayaoyao and Kiangan. Lambrecht argued that, since terrace inheritance was dictated by primogeniture, the active remembrance of familial ties would begin around the same time as terrace agriculture. His studies revealed Ifugao peoples could trace their lineage back ten generations, to roughly the seventeenth century, when the Magat river region depopulated (Lambrecht 1953, 1954). A later study of the *hudhud,* an epic poem of the Ifugao, seemed to locate the start of rice terracing in “Kiangan”, the site of Old Kiyyangan Village (OKV). Intriguingly, several references to firearms in the *hudhud* implied the legend was not ancient, but rather emerged after the Spanish conquest of the lowlands (Lambrecht 1967). Furthermore, Lambrecht’s work on the *hudhud* implied the lexicography describing terraces predated that epic, but that terraces only became extensive in Ifugao after the sixteenth century (Lambrecht 1967). Ultimately, this evidence bolstered Keesing’s hypothesis for the terraces’ “short-history”, but was not definitive proof—especially since Lambrecht exclusively studied oral culture, which is mutable.

 Although less concerned with the terraces’ origins, another famous scholar of the Cordillera, William Henry Scott, should be mentioned alongside Keesing and Lambrecht. Like Lambrecht, Scott arrived in the Philippines as a missionary, though he would later receive a PhD and become a prolific writer. His various essays on Cordillera architecture, agriculture, social differentiation, calendars, resistance, and history reflect more than three decades experience living in the Cordillera complemented by intensive archival research in Spain and the Philippines. His essays, as a result, are a mixture of ethnohistory and historical anthropology, and are cited extensively throughout this article’s methodology and thereby indirectly support the notion that the extensive terraces of Ifugao are a recent development (see Scott 1966, 1970, 1974, 1975, and 1982).

 At the same time as Scott was first publishing, anthropologist and ecological ethnographer Harold Conklin and his family were residing in Ifugao province. From nearly 17 years residing in the province, Conklin generated *The Ethnographic Atlas of Ifugao,* a singular text that describes (and maps) the contours of Ifugao ecology and agriculture as well as their effects on the rhythms of Ifugao life and spirituality. Although this work of ecological ethnography is principally focused on Northern Ifugao Province between 1963 and 1970, it also has a historical component, including comments by Conklin about the age of the terraces. He confirms Lambrecht’s observation that “the overall agricultural regime, in roughly its present form, undoubtedly extends back at least four centuries” (Conklin 1980, p. 38).

 Conklin’s concluding notes in the *Ethnographic Atlas* also make mention of radioactive carbon dating of a post used in terrace construction, which dated back to the 16th century (Conklin 1980). This data supported earlier archaeological investigations undertaken by Robert Maher near Banaue (northern Ifugao). Maher performed radioactive carbon dating of material from two separate residential terraces, with his results suggesting the terraces had been occupied for more than 1,000 years. As Maher noted, this old age did not preclude an expansion in terrace construction between 1570 and 1800 as argued by Keesing and Lambrecht, but did suggest that terracing was a long-standing practice in Ifugao (Maher 1973). Linguistic analysis performed two decades later would further confirm Maher’s observations, as Lawrence Reid’s analysis of Ifugao terracing terms indicated the words emerged from highland languages rather than being borrowed from lowlanders. Again, this suggested the terraces were an Indigenous invention, though Reid could not confirm whether the terraces were always used to grow rice or had been previously used for taro and other crops (Reid 1994).

 Most recently, the question of the terraces’ age has been revisited by Stephen Acabado, an anthropologist and archaeologist. Techniques developed by Acabado (2017) to reliably utilize radioactive carbon dating to assess terrace age and extensive archaeological fieldwork performed at OKV have permitted him to develop and advocate for a pericolonial history of Ifugao rice terraces. Acabado argues that the Spanish conquest indirectly influenced Ifugao highlanders, causing them to expand pre-existing terraces to support an increased population (perhaps a result of lowlanders or other Ifugao avoiding Spanish conquest). This expansion of pre-existing agriculture was complemented by a shift away from taro, which paleobotanic analysis suggests was the primary starch in OKV and Ifugao prior to the seventeenth century, in favor of rice, which became more prevalent as taro production seemingly decreased. As a result, Acabado argues, the terraces were both an indirect product of Spanish expansion but also a way to consciously reject subjugation to a colonial state, a pericolonial society (2017, 2018).

 In summation, the previous sixty years of scholarship have questioned the “long-history” theory of the terraces’ origins first advanced by Barton and Beyer, and now have provided viable, alternative theories including the pericolonialism hypothesis which this paper uses as a basis for historic land-use modelling.

**Supplement to 3.3.1: Population and Settlement Size at OKV**

In this subsection, we provide a brief overview of the available data on OKV’s population and size, and then detail viable ranges for these two parameters in both 1800 and 1570.

 After assessing the available accounts, which all speak of OKV as an especially large settlement, we chose to follow Acabado’s example and use Molano’s description from 1801 CE. Molano counted 186 houses in Kiyyangan (“Kiangan”), as well as multiple houses in adjoining villages: 10 in Murong, 20 in Pantakan, 28 in Dugang, and 40 in Paet while also noting that the hostile settlement of Burnay was “three leagues” away (12.54 km, assuming a standard *legua antigua*; Scott 1974; Acabado 2013). It is unclear whether Molano distinguished between the three house-like structures typical of traditional Ifugao architecture: the *bale* (a single-room, raised house), the ‘abung (an additional house for large families), and the ‘alang (a raised granary).

 Molano’s account and the IAP’s field work, undertaken in the previous decade, both indicate OKV had a defined nucleus. Acabado (2017) provides an outline of the nucleated OKV *boble* (settlement), locating its southwestern boundary along the Ibulao river. Based on Acabado’s findings, the old village’s nucleus circa 1570 approximated an ellipsis of area 1.70 ha. By 1800 CE, the village’s area had nearly doubled to 3.39 ha in size (ibid). For comparison, a hamlet called Buble in the Banaue-Ifugao region contained 46 individuals in 12 households in 1969. These twelve households, and their associated storage spaces and animals, occupied an area of ~0.2550 ha (Conklin 1980).

 Contemporary Ifugao settlement patterns and Molano’s account, though, prevent us from assuming the nucleus comprised the entirety of OKV. Ifugao settlements in the twentieth century are not concentrated, but exist as a series of hamlets scattered among *payo,* akin to Buble, though it is debated whether Ifugao settlements only recently adopted this idiosyncratic layout (Scott 1966). Further complicating matters, individual houses and settlements were and are constructed atop “residential terraces”, rice terraces that have been drained and converted to a space for homes, animals, and garden plants (Maher 1973; Conklin 1980). Therefore, the nucleus outlined by Acabado likely does not represent the full extent of OKV, especially if we accept that dispersed settlements are either a longstanding custom or emerged concurrently with extensive terracing to maximize families’ access to their *payo* and *muyong*.

 Given Molano’s account, Conklin’s description of Buble, Acabado’s research in OKV, and Maher’s discussion of terracing, we presume the total population of OKV in 1800 was dispersed throughout the terraced region to maintain a low population density and maximize access to terraces. We take this to mean OKV contained 284 houses, allowing that this may be an overestimate if Molano included additional structures. Given that a *bale* is a single room structure intended to hold an adult couple and young children, we assume an average occupancy between 3 and 4 individuals. This is supported by Conklin’s observations in Buble, where 46 people occupied 12 houses (3.83 people/house). It is also supported by Franklin Barton’s less detailed census of three villages in the Kiangan region—that includes OKV—at the turn of the 20th century, which identified 444 people living in 122 houses across three villages, or 3.63 people per house (Barton 1922; Conklin 1980). We conclude, then, that the population of OKV circa 1800 was between 852 and 1,136 individuals. Our template assumes OKV’s population was as high as possible, at 1,136 individuals.

 As for the “settlement area” this population would have required circa 1800, we presume the 3.39 ha nucleated settlement outlined by Acabado (2017) contained 186 houses and therefore 558 to 744 people (Scott 1974). Presuming the maximum population, we use Conklin’s (1980) observed density for Buble hamlet (0.0055 hectares per person or 180 people per hectare) to determine the remaining 98 houses would have required 2.16 ha. Ultimately, we estimate that OKV’s settlement terraces occupied ~5.55 ha in 1800 (the equivalent of 0.0049 ha/person, or ~205 people/ha).

 For the 1570 timepoint, our approximation is fully explained in the main paper (Methodology, section 3.3.1).

 It is worth noting that one could justify a wide range of settlement areas, based on the information we have presented here. There are, though, a few criteria that can determine whether the settlement area is plausible. The first is population density. Settlement terraces housed both people and domestic animals like dogs, pigs, and chickens. As population density increases past a certain point, such a living arrangement becomes unhealthy or, at some point, unrealistic. Given ethnohistoric evidence suggests that the Ifugao peoples managed to limit the spread of smallpox in their region (Scott 1974; Newson 2009), one expects the entire settlement’s population density would have been low (though density would have varied greatly on individual residential terraces or clusters of terraces). The second criterion is contemporary OKV’s ruins, where ~32 ha of land are currently terraced. Although the village was abandoned after 1832, smallholders continue to use the land (Acabado 2017). Presumably, these smallholders are utilizing terraces once used in OKV. Therefore, given the viciousness of Galvey’s sack of OKV in 1832, which targeted terraces as much as homes, one would expect the existing 32 hectares of terrace are a fraction of the land once terraced to sustain OKV. Therefore, the combined area of the settlement and *payo* in our circle diagrams for 1800 should exceed 32 hectares (or, given our logic, 16 hectares in 1570).

**Supplement to 3.3.1: *Bale* and Land Use**

In the Ifugao region, the *bale* and other Indigenous structures were made entirely of organic, perishable materials. Villages were primarily composed of *bale* accompanied by ‘*alang* (raised granaries)and, in the case of an especially large family, *‘abang* (unraised houses)*.* The *bale,* described thoroughly by W.H. Scott, is an elevated structure with a single square room and a large, sloped roof that extends down past the walls to the posts. The posts and foundation of the structure are composed of hardwoods, while the roof is comprised of grasses. The roof and bark walls are routinely replaced, while the hardwood foundations and supports can endure for generations. A *bale* is also a highly mobile structure, being able to be deconstructed and reassembled in a single day. The interior is unfailingly described by ethnographers as eye-wateringly smokey, as a ceaseless fire sits at the structure’s center. The structure is primarily used for cooking and sleeping, with its primary occupants being a married couple. In addition, any small children not yet of marriage age will also live in the *bale*. While the *bale* does have interior storage, large amounts of grain are stored in *‘alang’,* which resemble smaller variants of the *bale* (Scott 1966). All these structures require materials found in grasslands and *muyong*. However, the annual material requirements of Ifugao houses and granaries are insignificant relative to fuel and agricultural requirements and are therefore excluded from our models (Conklin 1980; Ipac-Alarcon 1991). As a result, houses do not add to the amount of land we calculate must be allotted to *muyong.*

**Supplement to 3.3.2: Terrace Agriculture**

 The *payo* are typically constructed at lower elevations (below 1600 m above sea level), are close to settlements, have ease of access to water, and constitute an extraordinary investment of time and labor. Rice from the terraces is a prestige crop with profound religious significance, its cultivation and harvest defining the traditional Ifugao annual calendar (Conklin 1980). In the months separating the harvest and seeding of rice, terraces are repaired, maintained, constructed, or expanded as necessary, with all terraces being fertilized using vegetable mulch prior to the start of rice cultivation. Functioning terraces maintain an artificial wetland environment that permits rice and, if desired, taro cultivation, but also support a range of freshwater mollusks and fish that are a vital protein source for Ifugao peoples. As a result, they do not require fallow periods (Conklin 1980; Bray 1994). Furthermore, the bunding that tops terrace walls can be used to grow legumes, while pathways between terraces are often used to cultivate root crops (Conklin 1980). Therefore, in our models we do not expect any terraced land to be unused, and we expect most legumes and vegetables (including squashes) were grown along terrace pathways or bunding, meaning they did not contribute to OKV’s total land use.

**Supplement to 3.3.9: Yield and Nutritional Value**

Circle diagrams employ crop yields to determine the effects of a population’s distinctive “lifestyle” on land-use. However, determining historic yields for crops and animals is notoriously difficult. Much of the way the world currently accounts for and measures food production is intricately linked to the Green Revolution and 20th century American perspectives on agriculture, production, and land management (MacRae 2016; Reuter 2018). Key to the Green Revolution’s self-rationalization and continuation is the measurement and improvement of agricultural yield, ideally without requiring the expansion of agricultural land and pasture into previously unutilized, threatened environments (Greenland 1997). However, reliable and continuous records of crop productivity outside Europe and North America are only available after the Green Revolution began, from the 1960s onwards (FAOSTAT 2021).

Sporadic data on crop productivity is available for some of the world in the 20th century, including parts of the Philippines that experienced American colonization (Greenland 1997). These intermittent records of productivity in the 20th century, however, cannot be directly applied to the distant past. The nineteenth century witnessed the advent of various fertilizers, including ammonium and phosphates, which increased field nutrient availability while reducing fallow periods, permitting increases in yield and more intensive land-use. However, these fertilizers were applied irregularly throughout the colonized world (see Cushman 2013). Therefore, this section of the Supplementary Material outlines how we determine the productivities and caloric values of various crops and animals, following the procedure we discussed in the Methodology (section 3.3.9).

*Rice*

Owing to its prominence in the Green Revolution historic yields for rice are, compared to other species on this list, relatively well-known. The maximum yield of rice prior to inorganic fertilizers and modern varieties, according to Francesca Bray’s *The Rice Economies,* is2.0 t/ha (1994). Greenland, former vice president of IRRI, compiled a table of rice yields for various Asian countries, including the Philippines. Philippine yields from 1913-1917 (the earliest time point Greenland provides) were 0.78 tons/hectare, increasing gradually to 1.3 tons/hectare between 1963 and 1965. In 1975-1977, after the introduction of IR8, the yield increased to 1.9 tons/hectare, ultimately achieving yields of 2.8 tons/hectare between 1990-1993, surpassing Thailand’s and India’s average yields (Greenland 1997). When establishing a potential minimum yield for historic rice, we exclude the 1913-1917 estimate of 0.78 t/ha because it is unclear how reliable measurements were at the start of the American colonial period.

Ifugao terraces, though, are known to have high variability in productivity. Conklin assessed productivity in 10 terrace-fields from 1963 to 1970 and determined their average productivity was 2,500 kg/ha, or 2.5 tons/hectare (1980). The average yields of each pond varied from 1432 kg/ha to 3175 kg/ha, and the inundated area of each pond did not directly correspond to yield. It is also unclear if inorganic fertilizers were employed in these ten terraces, though it seems unlikely since Conklin made no mention of them.

 Given our uncertainty regarding Conklin’s numbers, we set rice’s productivity to the average between Greenfield’s reported yield for 1963-65 (1.3 t/ha) and Bray’s historical maximum (2.0 t/ha) in our template model: 1.65 t/ha. Later in the Supplementary Materials, however, we also employ Conklin’s reported average of 2.5 t/ha to explore the uncertainty in our models.

*Taro (aba)*

Taro (*Colocasia esculenta*) is theorized to have been the primary staple food of Ifugao peoples prior to the Spanish arrival in Luzon (Acabado 2012a, 2017) and is still intercropped in terraces and swidden fields (Conklin 1980), having retained ceremonial import. Modern yields range from 2 to17 tons/ha (Wilson and Siemonsma 1996). While historic yields for Ifugao were not readily available to us, an ethnographic investigation by Peralta of the I’wak, the only peoples in the Cordillera that grow taro as their primary starch in the present day, indicates Cordillera taro’s yield is very low: 273 kg/ha (Peralta 1982, cited in Acabado 2012a). However, the yield Peralta indicates is an outlier, and might not be applicable to the fertile soils of Ifugao. Therefore, we assume Ifugao taro had a productivity of 2 t/ha.

*Purple Yams (Iuktu)*

Purple yams (Dioscorea alata L.) were and are a popular starch in the Philippines, distinguished by their deep-purple flesh (although the flesh may be red or white as well). Like sweet potatoes, purple yam readily grows in swidden fields, preferably in raised ridges, as is common practice in twentieth century Ifugao swidden fields (Conklin 1980). It is relatively drought resistant, able to grow to maturity with as little as 1,300 mm annual precipitation. To ensure tubers grow to maximum size, it is recommended they be planted at the start of the rainy season (June in Ifugao). However, purple yam grows best at low and medium elevation; high elevation can severely reduce yields. Using modern fertilizers in Luzon soils, the Philippine Department of Agriculture assumes purple yams will achieve a yield of 30 t/ha, with an average weight of 100 grams per yam (Bacquira 2012). However, Tulin in 2009 indicates that purple yams cultivated in the Philippines have an average yield of only 5 t/ha, in large part because modern fertilizers and growing techniques emphasizing productive efficiency are not frequently employed by small-scale farmers (Tulin 2009). Given Tulin’s assessment, we assume historic yields for purple yams were 5 t/ha in Ifugao.

*Sweet Potato/Camote*

Sweet potato, or camote, is an American starch that was introduced to the Philippines through the annual voyage of the Manila Galleons (Amano et al 2020). Unlike the other American staple crop, maize, sweet potato was rapidly incorporated into Philippine diets (Vandermeer 1967). This may be attributable to its similarities to *iuktu.* In 20th century Ifugao, sweet potatoes are now the staple swidden crop, feeding most Ifugao peoples throughout the year (Conklin 1980). However, it is difficult to determine whether the crop was grown extensively in Ifugao circa 1800. Friar Antolin in 1789 compiled several sources claiming the peoples of Benguet grew *camote* as well as *iuktu* and *aba* (Antolin and Scott 1970). Complicating Antolin’s interpretation is William Henry Scott’s preliminary reports from 1958, when he noted that sweet potatoes began to replace taro as the primary swidden crop in Benguet during the Spanish-American war (Scott 1966). And, it was not uncommon for Spanish observers to mistake yam for sweet potatoes (Amano et al 2020).

Therefore, our template model assumes sweet potato and purple yams were present in equal proportions in 1800. Sweet potatoes grown in Asia have inconsistent yields, ranging from 2 to 22 t/ha (PROSEA). In the *Ethnographic Atlas of Ifugao,* Conklin (1980) observed sweet potatoes—seemingly grown without fertilizers—achieved a productivity of 6.5 t/ha. The average productivity of sweet potatoes in the Cordillera Administrative Region (CAR), as measured by the Philippine Statistics Authority (2018), recorded a slightly lower average yield of 5.15 t/ha across the whole of the Cordillera. Given that sweet potatoes ultimately usurped purple yams in Ifugao diets, we expect sweet potatoes had at least a similar productivity to sweet purple yams. Given this information, our model assigns sweet potatoes a productivity of 6 t/ha, between Conklin’s observed productivity for Banaue, Ifugao and the Philippine Statistics Authority’s average for the whole Cordillera. This estimate slightly favors Conklin’s observed productivity, since it is more specific to the Ifugao region.

*Banana*

 Various banana species are indigenous to the Philippines. According to Valmayor et al (2002), the five most prominent in the twenty-first century are Bungulan, Lakatan, Latundan, Pelipita, and Saba. Bungulan, confusingly known as Lacatan in Central and South America, is a variety of Cavendish Banana primarily grown in Mindanao for the export market, and is not especially popular for local cooking or consumption (Valmayor et al 2000, 2002). Philippine Lakatan and Latundan bananas are desert bananas, whereas Pelipita is a cooking banana (Valmayor et al 2002). The Saba varieties, meanwhile, are especially popular in the Philippines for cooking, with the Carbada variety being widespread in the Visayas and Mindanao. Another variant, known as *Dippig* in Ilocos and Saba generally, is widespread in Luzon, including in the north (Valmoyor et al 2000, 2002).

 It is unclear which varieties of banana tree were utilized in Ifugao in the sixteenth or eighteenth centuries. However, publicly available crop statistics for the Philippines indicate that, in the twenty-first century, Cavendish bananas are not grown in the CAR at all. Instead, Lakatan and Saba varieties are planted in small amounts, likely for local consumption. From 2013 to 2017, average Lakatan production was 4,226 metric tons on 880 hectares of land for an average yield of 4.80 t/ha. Average Saba production in the CAR for the same period was 8,817 metric tons on 1,244 hectares of land for an average productivity of 7.087 t/ha (Philippine Statistics Authority 2018). Both numbers fall within the wide range of modern banana productivities identified by PROSEA, which vary from 3 to 60 t/ha (Espino et al 1991).

 Given these numbers, the realistic range for Saba growth in OKV would be 3.00-7.087 t/ha, and the realistic range for Lakatan varieties would be 3.00-4.80 t/ha. Presuming banana trees were integrated into *muyong* woodlots, multiple varieties of banana were grown, and all enjoyed varying success, no specific yield will be entirely satisfactory. We therefore will assume that Saba varieties predominated in the Cordillera, and these enjoyed a lower productivity than present breeds, using the median yield of 5.07 t/ha.

*Arrowroot and Breadfruit*

 Acabado (2017) indicates arrowroot and breadfruit were present at the OKV based on phytolith analysis, but only in trace amounts. Therefore, Acabado suggests these crops were not actively cultivated at the OKV. As with sweet potato, we do not ascribe a significant portion of Ifugao diets to these two crops.

*Squash (Kalabasa)*

 *Kalabasa* was the most prominent vegetable in Ifugao agriculture according to available historical sources, being frequently grown in swiddens in Cordillera provinces bordering present-day Nueva Vizcaya province (Antolin and Scott 1970). The variety of squash that Antolin refers to, though, is unclear. According to the “Squash Production Guide” produced by the Philippine Department of Agriculture, *kalabasa* most frequentlyrefers to *Cucurbita maxima*, which grows well on ridged fields akin to those used in Ifugao and has an expected yield of 12.0 and 21.8 t/ha (Tepper 2013). Lacking a range for historic yields, we instead use the modern minimum of 12.0 t/ha.

**Supplement to Section 4: Scenarios for the 1800 Model**

As our methodology indicated, our template circle diagrams represent a probable land use pattern, based on several hypotheses regarding population, crop yields, diet, surplus production, and commerce. This section explores how varying these parameters affects land use to produce plausible, if less probable, patterns. Put differently, these scenarios explore the uncertainty in our model calculations and diagrams. We limit our discussion to *kadangyan* and *nawotwot* in 1800 CE, since there is more data available for this period.

### *Population and Annual Caloric Requirements*

All of our model calculations are directly related to a settlement’s population and its calculated caloric requirements. Variation in either parameter causes ubiquitous, linear changes. If, as we discussed in section 3.3.1, we decrease OKV’s 1800 CE population by 25% to 852, the result is nearly all forms of land use decrease by 25% (see Supplementary Figure 1). Similarly, annual caloric requirements affect all forms of land use directly related to agriculture, animal husbandry, and hunting (but not the Settlement size or wood use). Therefore, increasing individuals’ average daily caloric need from 2234 kcal (815410 kcal per year per person) to 2,600 kcal (949,000 kcal per year per person) causes non-uniform growth in land use (Supplementary Figure 1).

### *Rice Productivity*

 A point of great uncertainty in these models is the historic yield of various crops. In Supplementary Figure 1, we demonstrate how land use would decrease if rice’s expected yield were increased from our initial estimate of 1650 to 2500 kg ha-1, the yield Conklin (1980) observed in mid-twentieth century Ifugao terraces. If this scenario proved historically accurate, it would suggest that the terraces and Ifugao land use were more efficient than our template diagrams suggest.

### *Yams and Camote*

A second point of uncertainty is when sweet potatoes replaced yams as the primary root crop in OKV. The scant evidence available suggests that this process was underway by 1800 CE (see section 3.3.3). Our template reflected this transition by suggesting half the root crops consumed in OKV were purple yam, while the other half were sweet potato. If we assume instead that sweet potato had replaced yam entirely by 1800, then the amount of swidden fields OKV used each year would decrease (see Supplementary Figure 1). Alternatively, if we assume only yams were grown in 1800, the amount of land required for swidden fields would increase relative to our template (Supplementary Figure 1). Whatever the case, though, rice terracing would be more efficient than swidden farming—particularly once fallow fields are considered. However, the introduction of sweet potatoes in OKV would have further condensed land use in the village, allowing more people to live on less land, even while using the same swidden techniques used to grow yams.

### *Failed Rice Crop*

 Our model can also be utilized to depict poor harvest years as well as the effects of natural hazards and prolonged famines. In Ifugao, frequent typhoons can inflict severe damage to rice terraces, jeopardizing a portion of the harvest. In Supplementary Figure 1, we model a year where 100% of a rice harvest was lost. Such destruction would have prompted a rapid expansion of swidden fields, with *kadangyan* relying on tubers to supplement their reduced rice stores (Conklin 1980). This would have increased land use temporarily, promoting the clearing of unowned, forested land.

 It should also be noted that a typhoon that caused such extensive damage would undoubtedly have affected OKV’s commerce with other highland peoples and with lowlanders. The loss of rice, their primary trade good, would have been a temporary disadvantage. Presuming the *kadangyan* maintained a surplus of rice in granaries (‘*alang*), commerce would have continued, perhaps serving as a vital source of food—especially if a typhoon disturbed domesticated animals or prevented OKV’s residents from collecting fish and shellfish from the remaining terraces. However, given the significance of trade in Ifugao and the Philippines more broadly, it is doubtful a typhoon, a relatively common occurrence in the Ifugao, would prevent commerce.

### *Goats and Carabao*

Although goats were common in the Philippines (Amano 2020), there is no confirmed evidence of them in OKV. Therefore, we did not include them in our template. In Supplementary Figure 2, we add them to our template as a small portion of the diet (0.1%, the same as carabao). Nonetheless, that small proportion of goat would have required ~158 animals, who would have subsisted on ~131 ha of land. This scenario would make the Ifugao land use system markedly less efficient.

Alternatively, in Supplementary Figure 2 we depict Ifugao without either goats or carabao. In this scenario, we assume all carabao were purchased from the lowlands with surplus rice. As a result, 0 ha of pastureland would be required by the village, and land use would be more efficient than in our template. It should be noted, though, that neither of these scenarios change our fundamental conclusion: land use in 1800, through the introduction of terraces, became more condensed at some time between 1570 and 1800 and seemingly without requiring increased deforestation.

*Expansive Hunting*

 Our models calculate the land available for hunting based on a region’s presumed population density and the percentage of a settlement’s diet fulfilled by hunting. This can be done using either on site data or—if that data is not available—population densities established by Binford (2001) to describe Indigenous land use. For Ifugao in 1800, no Binford population density exists, so we calculated the region’s population density based on information contained in the 1903 census, the earliest count of the entire Cordillera Administrative Region’s (CAR) population available. Therefore, for the 1800 timepoint, our models assume regional population density in the OKV area was 514.8 individuals per 100km2. This means the 1,136 individuals residing in OKV who derived 6.3% of their annual calories from wild game hunting would have hunted on 1,390 ha. If we instead used one of Binford’s observed population densities for Philippine Indigenous peoples, such as the Aetas of Morong (90 people/100 km2; Binford 2001), then our model would argue OKV utilized 7952 ha of land for hunting (Supplementary Figure 3).

 Given available information, both of these numbers are feasible. If 1,390 hectares is imagined as a circle, its radius would be 2.10 km. Likewise, a circle of area 7952 hectares would have a radius of 5.03 km. Despite Ifugao’s rugged terrain, the full diameter of these imagined circles could be traversed in a single day, even while carrying a killed and field-dressed deer—one whose head, intestines, and (perhaps) legs had been removed immediately after it was killed.

Additionally, evidence suggests historic populations of Philippine deer, *R. marianna,* could have endured intensive hunting. Modern populations of *R. marianna,* particularly in protected spaces, have achieved minimum measured population densities of 60-80 individuals per km2 (Ali et al 2021). If the estimated usable meat on *R. marianna* is 26.74 kg (assuming the animal’s live weight was 68 kg), then OKV would have required 623 individuals per year to provide a population of 1,136 people 1.6% of their diet (Ali et al 2021). These deer would have required between 7.79 and 10.4 km2 of forests and grassland to subsist. Since two deer produce one fawn per season, that land area must at least be doubled to permit a sustainable population. Therefore, the number of deer required by OKV would have inhabited a space of 1,558 to 2,080 hectares, presuming minimum observed density (an unpublished military report suggests populations could reach as high as 183 deer per km2; see Ali et al 2021). Therefore, while 1,390 hectares may represent an underestimate for hunting space, it is still a plausible estimate for the lowest intensity activity we consider in our models.

# Supplementary Figures

Supplementary Figure 1: Circle diagrams depicting scenarios for the 1800 timepoint. Panel A is the template diagram presented in the main results; Panel B models OKV with a population of 852, lower than the template; Panel C models OKV if every individual consumed 2,600 calories per day, more than in the template; Panel D models OKV if rice’s presumed yield is 2,500 kg/ha, higher than in the template; Panel E models OKV if only yams were grown instead of yams and sweet potatoes; Panel F models OKV if only sweet potatoes were grown instead of yams and sweet potatoes; Panel G models OKV if it lost a single year’s rice harvest to a sudden, destructive natural hazard; and Panel H provides a scale and legend for interpreting the diagrams.

Supplementary Figure 2: Circle diagrams depicting scenarios for the 1800 timepoint. Panel A is the template diagram presented in the main results; Panel B models OKV if a small goat herd was present; Panel C models OKV if no carabao herd was kept in the village; and Panel D provides a scale and legend for interpreting the diagrams.

Supplementary Figure 3: Circle diagrams depicting scenarios for the 1800 timepoint. Panel A is the template diagram presented in the main results; Panel B is an alternate hunting scenario that assumes a much lower population density; and Panel C provides a scale and legend for interpreting the diagrams.

# Supplementary Tables

**Supplementary Table 1:** Starches and vegetables commonly grown in OKV circa 1570 and 1800. The crops’ English names are listed in bold with local names in parentheses. For each crop, we provide its Latin name, whether it was present in OKV in 1570 and 1800, and the sources we consulted.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Crop Name** | **Latin Name** | **Present in 1570?** | **Present in 1800?** | **Source** |
| **Wet Rice****(tinawon)** | *Oryza sativa* | Yes (in low quantities). | Yes | Antolin and Scott 1970; Acabado et al 2017; Horrocks et al 2018; Acabado 2017 |
| **Sweet Potato****(*gattuk*)** | *Ipomoea batatas* | No | Unclear, not confirmed by charcoal residue.  | Antolin and Scott 1970 |
| **Taro (*aba*)** | *Colocasia esculenta* | Yes | Yes | Antolin and Scott 1970; Acabado 2017, 2012a, 2012b |
| **Purple Yam (*iuktu*)** | *Dioscorea alata L.* | Yes | Yes | Antolin and Scott 1970; Horrocks et al 2018  |
| **Banana** | *Musa spp*. | Yes | Yes | Antolin and Scott 1970 |
| **Arrowroot** | *Pueraria montana* | Yes (in non-significant amounts) | Yes (in non-significant amounts) | Acabado 2017; Horrocks et al 2018 |
| **Breadfruit** | *Artocarpus altilis* | Yes (in non-significant amounts) | Yes (in non-significant amounts) | Acabado 2017; Horrocks et al 2018 |
| **Squash (Kalabasa)** | *Cucurbita maxima* | No | Yes | Antolin and Scott 1970 |

**Supplementary Table 2:** Animals (domestic and wild) confirmed present in OKV circa 1570 and 1800. The table provides each animal’s English name, Latin Name, confirms whether it was present in 1570 and in 1800, provides a list of sources consulted, and additional notes if required.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Animal Name** | **Latin Name** | **Present in 1570?** | **Present in 1800?** | **Source**  | **Notes** |
| **Domestic Pig** | *Sus scofra* | Yes | Yes | Antolin and Scott 1970; Acabado 2017; Ledesma et al 2015. | Presence of domestic pig increases after 1570 |
| **Chicken** | *Gallus gallus* | Yes | Yes | Antolin and Scott 1970; Acabado 2017; Ledesma et al 2015 |  |
| **Dog** | *Canis familiarus* | Yes | Yes | Acabado 2017; Ledesma et al 2015 | Used for hunting. |
| **Wild Pig** | *Sus philippensis* | Yes | Yes | Acabado 2017; Ledesma et al 2015 |  |
| **Wild Deer** | *Rusa marianna*  | Yes | Yes | Acabado 2017; Ledesma et al 2015 | Previously known as *Cervus mariannus* |
| **Domestic Carabao** | *Bubalus bubalis* | No | Yes | Antolin and Scott 1970; Acabado 2017; Ledesma et al 2015 | Prestige animal, owned by *kadangyan.*  |
| **Misc.** |  | Yes | Yes | Ledesma et al 2015; Conklin 1980; Barton 1922 | Monkeys, snakes, monitor lizards, small mammals, freshwater shellfish and fish. |

**Supplementary Table 3:** Estimated productivity of significant crops in OKV circa 1570 and 1800. Provided for each crop is the its lowest and highest expected yields according to available literature (see Supplementary Materials) and the assumed yield employed in the circle diagrams.

|  |  |  |  |
| --- | --- | --- | --- |
| **Crop** | **Determined Min. Yield (t/ha)** | **Determined Max. Yield (t/ha)** | **Assumed Yield for Modelling (t/ha)** |
| **Wet Rice** | 1.3 | 2.0 | 1.65 |
| **Taro** | 2.0 | 17 | 2.00 |
| **Purple Yam** | 5.0 | 10.32 | 5.00 |
| **Banana** | 3.0 | 7.087 | 5.07 |
| **Squash** | 12.0 | 21.8 | 12.0 |

**Supplementary Table 4:** The caloric content of foods known to be significant to Ifugao diets circa 1570 and 1800. In each row, we provide the English name of an animal or plant, its caloric energy content, the source of our information, and any pertinent notes. Note that the CINE source refers to Santos-Acuin et al 1997.

|  |  |  |  |
| --- | --- | --- | --- |
| **Name of Flora/Fauna** | **Energy (Cal/kg)** | **Source** | **Notes** |
| **Domestic Pig** | 2370  | CINE | Raw Tenderloin |
| **Chicken** | 1730 | CINE  | White meat, boiled |
| **Wild Pig** | 2370 | CINE | Raw Tenderloin |
| **Wild Deer** | 890 | CINE | Leg and Rib, raw |
| **Domestic Carabao** | 1240 | CINE  | Low fat portions, boiled |
| **Chicken Egg** | 1600 | CINE |  |
| **Misc. Wild Game** | 1201 | Kay and Kaplan 2015 |  |
| **Mudfish** | 830 | CINE | Raw |
| **Wet Rice** | 3540 | CINE | Raw |
| **Sweet Potato** | 1320 | CINE | Raw |
| **Taro** | 1110 | CINE | Raw |
| **Purple Yam** | 950 | CINE | Raw |
| **Banana** | 1080 | CINE | Saba variety |
| **Squash** | 410 | CINE |  |