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# A spatiotemporal model of risk and uncertainty for Hawaiian dryland agriculture and its implications for *ahupua'a* community formation

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ABSTRACT

The Hawaiian Islands, like many other high volcanic islands, are characterized by a diversity of ecozones, which had ramifications for the types of subsistence strategies that developed within each. Although traditional cultivation practices were highly variable, agricultural systems can be roughly split into windward and leeward forms. Leeward agriculture is differentiated from windward agriculture based on the almost complete dependence on rainfall. Dependence on rainfall, an often-unpredictable resource, creates a high level of risk and uncertainty in agricultural yields. Dryland field-systems were highly susceptible to droughts, potentially resulting in food shortages that would have had various societal consequences, such as increased intergroup conflict, community cooperation, or social inequality. The concepts of risk and uncertainty, derived from human behavioral ecology, are useful for exploring how fluctuations in the availability of resources from droughts influenced agriculturalists in the Hawaiian Islands. Using the Rainfall Atlas of Hawai‘i, a newly published rainfall archive, we investigate spatiotemporal rainfall patterns in the Leeward Kohala Field System (LKFS) on Hawai‘i Island. We employ geostatistical modeling techniques, time-series analysis, and a simulation model to quantify the intensity, frequency, and periodicity of droughts in the LKFS. Our results support previous studies and suggest a high degree of agricultural risk, particularly from ca. AD 1450–1600, with implications for Hawaiian agriculture and emerging sociocultural patterns.

## 1. Introduction

Prehistoric agriculture in Oceania is typically divided into two contrasting systems of wetland and dryland cultivation (Kirch, 1994). Wetland agriculture exploits permanent or semi-permanent water sources through the construction of pond-field or raised-bed irrigated systems (Kirch, 1977; Kirch and Lepofsky, 1993). These wetland agricultural systems provided a high and essentially constant crop-yield, and were therefore predicable and relatively risk-free (Kirch, 1994). Dryland agriculture, in contrast, was almost completely dependent on rainfall and is described as labor intensive and highly variable in yield (Kirch, 1994; Lee et al., 2006). Despite these disadvantages, dryland agriculture played an important role in the political economy and evolution of social complexity in Oceania (Kirch, 1984, 1994). The dynamic relationship between societal change and dryland subsistence practices is an especially important topic in the archaeology of the Hawaiian Archipelago, and the large dryland agricultural systems of Maui and Hawai‘i Island have figured prominently in these discussions (e.g., Kirch 2010b; Kirch et al., 2004; Vitousek et al., 2004, 2014).

Building on a wealth of previous investigations (e.g., Diaz et al., 2016; Kirch et al., 2012; Ladefoged et al., 2008, 2009, 2011; Ladefoged and Graves, 2008; Lee et al., 2006; Vitousek et al., 2004), in this paper we investigate risk and uncertainty in Hawaiian dryland agriculture by modeling the spatiotemporal occurrence of droughts in the Leeward Kohala Field System (LKFS), a large 60 $km^2$ prehistoric dryland agricultural complex on Hawai‘i Island (Fig. 1). We use 81 years of historic rainfall measurements from the Rainfall Atlas of Hawai‘i (Frazier et al., 2016; Giambelluca et al., 2013) to construct a geostatistical model of drought estimates for the entire LKFS. We also apply time-series analyses of drought uncertainty and a simulated paleoclimate reconstruction from AD 1301–1900. We parameterize our model based on the minimum annual rainfall requirements of sweet potato (*Ipomoea batatas*), the main crop grown in the LKFS (Ladefoged and Graves, 2010).

Our study complements previous approaches by providing a theoretically explicit investigation of risk and uncertainty, in combination with the use of a large, spatially and temporally extensive empirical dataset, and a robust geostatistical model of past climatic variation. Our findings suggest that the risk of droughts is spatially patterned and

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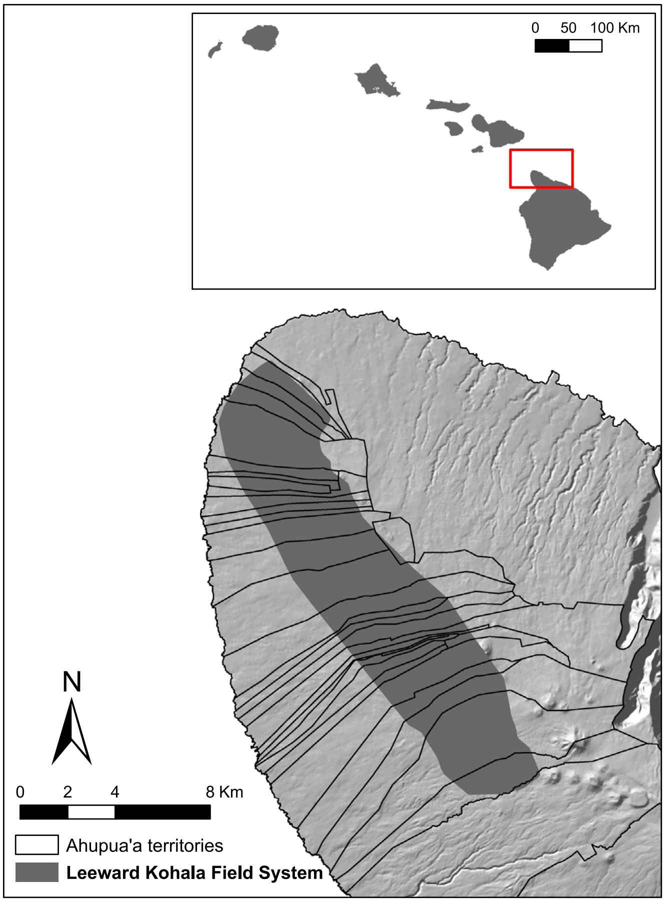


**Fig. 1.** Location of the Leeward Kohala Field System on Hawai'i Island.

likely would have occurred frequently in the LKFS, possibly at unpredictable intervals. Drought risk and uncertainty in the LKFS during Hawaiian prehistory would have had important implications for prehistoric Hawaiian agriculture and emerging sociocultural processes, such as intergroup aggression, community cooperation, and economic inequality, which we discuss in more detail below.

## 2. Background

### 2.1. The concepts of risk and uncertainty

We ground our approach in human behavioral ecology (HBE), the study of how human behavior evolves in response to various socio-ecological conditions. HBE as a theoretical framework is useful here because it guides both our explanatory and analytical approach to risk and uncertainty. While both risk and uncertainty are related to environmental stochasticity, the concepts are theoretically and analytically distinct. *Risk* refers to the degree of variation in the outcome of some decision, whereas *uncertainty* refers to an individual's lack of information about the outcome (Cashdan, 1992; Low, 1990; Smith, 1988). The difference between risk and uncertainty has important analytical ramifications. For example, when the outcome of different strategies is known (i.e., low uncertainty), one may still have to cope with variation in possible outcomes (risk) (Smith, 1988: 231). If the frequency of food shortages through time is subject to a high degree of variability but this variability is predictable, then individuals can respond by relying on other resources when shortages are likely (Low, 1990). However, these risk-buffering strategies are less useful when uncertainty is high since information to counter unpredictable environmental fluctuations may not be available.

When observed at a population scale, individuals are expected to pursue subsistence strategies that minimize both risk and uncertainty (Cashdan, 1992; Smith, 1988; Stephens, 1990; Stephens and Charnov, 1982; Winterhalder, 1986, 1990). While minimizing risk may simply require gaining information regarding variability, coping with uncertainty is often more difficult. Uncertainty involves (un)predictability, which is associated with two related concepts – *constancy* and *contingency* (Cashdan, 1992; Colwell, 1974; Low, 1990). If a resource shows very low variation over time, then it is predictable because of its constancy; if the resource exhibits large amounts of variation but does so depending on the occurrence of some other more predictable event, then it is predictable because of contingency (Cashdan, 1992: 238). When a resource is unpredictable, then individuals are expected to pursue a range of different coping strategies which average out spatiotemporal variation, such as mobility, reciprocal resource exchange, information sharing, storage, or increased diet breadth (Cashdan, 1990, 1992; Halstead and O'Shea, 1989; Kaplan et al., 1990; Smith, 1988; Smith and Boyd, 1990; Winterhalder, 1990).

Risk emerges from variation in the outcome of an event, such as the productivity of a crucial resource (Smith, 1988:231). In agriculture, if the outcome of planting crops varies greatly between high crop yield and crop failure, then this activity includes a high degree of risk. If agricultural success is closely tied to rainfall, then measuring the spatiotemporal frequency of droughts is a proxy for agricultural risk, as the effect of a drought is either to greatly reduce yield or in the worst-case scenario, cause crops to completely fail. Furthermore, evaluating whether there are predictable cycles in these drought events provides a measure of the uncertainty involved with these risks, since events that reoccur at short and regular temporal frequencies are predictable and therefore decrease the level of uncertainty. Prolonged agricultural risk and uncertainty have minimally two important ramifications for agriculturalists. First, the persistence of spatially patterned risk can lead to economic inequality, as some areas consistently fail to produce the crop yields at the same levels of other areas (Boone, 1992; Mattison et al., 2016). Second, among agriculturalists, especially in tropical regions, there is a common pattern of reciprocal resource exchange between households or communities as a risk buffering strategy (Piperno, 2011: S466; Winterhalder 1997: 153). Depending on the spatial scale, such a scenario may result in both reciprocal resource exchange and also the development of unequal social contracts in the form of patron-client relationships or 'managerial mutualism' (Boone, 1992; Mattison et al., 2016; Smith and Choi, 2007). Together, these predictions suggest that spatially patterned agricultural risk and uncertainty have a strong influence on both the development of cooperation within communities and conflict or inequality between them.

### 2.2. Subsistence and community patterning in the Leeward Kohala Field System (LKFS)

The diverse ecology and climate of the Hawaiian Archipelago presented prehistoric populations with various subsistence opportunities, ranging from marine foraging (Morrison and Hunt, 2007; Field et al., 2016) to intensive irrigated and dryland agriculture (Ladefoged et al., 2009). Of these different subsistence strategies, dryland agricultural systems have received considerable attention. The large dryland field systems of the Hawaiian Islands are typically located within "sweet spots" of rainfall and soil fertility on leeward volcanic slopes (Baer et al., 2015; Ladefoged et al., 2009; Vitousek et al., 2004). Compared to wetland and irrigated agriculture, both ethnohistorical descriptions and recent archaeological studies suggest that dryland agriculture had lower average yields, required more labor input, and was more prone to droughts (Kamakau, 1992; Lee et al., 2006; Malo, 1987: 204). Despite these drawbacks, dryland agriculture was widely practiced and is often argued to be an important driver in the rise of socio-political hierarchies and territorial expansion late in Hawaiian prehistory (Graves et al., 2010; Kirch, 1984, 1994, 2010a, 2010b; Ladefoged and Graves, 2000, 2008). Of the large Hawaiian dryland field systems, the LKFS has