PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B

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Research

The influence of social niche on cultural niche construction: modelling changes in belief about marriage form in Taiwan

Mikhail Lipatov[2,3,4,†], Melissa J. Brown[1,3,*,†] and Marcus W. Feldman[2,4]

[1]*Department of Anthropology,* [2]*Department of Biology,* [3]*Institute for Research in the Social Sciences, and* [4]*Morrison Institute for Population and Resource Studies, Stanford University, Stanford, CA 94305, USA*

With introduction of social niche effects into a model of cultural change, the frequency of a practice cannot predict the frequency of its underlying belief. The combination of a general model with empirical data from a specific case illustrates the importance of collaboration between modellers and field researchers, and identifies the type of quantitative data necessary for analysing case studies. Demographic data from colonial-period household registers in Taiwan document a shift in marriage form within 40 years, from a mixture of uxorilocal marriages and virilocal marriages to the latter's dominance. Ethnographic data indicate marriage-related beliefs, costs, ethnic effects and colonial policies as well as the importance of horizontal cultural transmission. We present a formal model for the effects of moral beliefs about marriage and a population economic index on the decline of uxorilocal marriage. We integrate empirical marriage rates and an estimated economic index to produce five projections of the historical frequencies of one belief. These projections demonstrate how economic development may affect a cultural niche. They also indicate the need for future research on the relationship between wealth and cultural variability, the motivational force of cultural versus social factors, and the process of cultural niche construction.

Keywords: horizontal cultural transmission; economic index; uxorilocal marriage; virilocal marriage; colonial household registers; cultural change

1. INTRODUCTION

Humans are inextricably social and cultural animals. We are, each of us, born into a particular society with its specific structure and a particular culture with its specific languages and beliefs. For humans, then, society and culture constitute niches at least as much as the ecological environment. Other scholars of this issue discuss ways in which aspects of human societies and cultures have constructed the ecological niches in which people live. Here, we view the theory of niche construction within the realm of human society and culture in order to explore how these niches—which can powerfully influence the ecological environment and genetic evolution (e.g. [1,2])—are themselves constructed and passed on by humans who live within them.

We view the social niche of a population as the sum of all the social selection pressures to which the population is exposed and the cultural niche of a population as the sum of all the cultural selection pressures to which the population is exposed (modifying the definition of an ecological niche from Odling-Smee *et al.* [1]; see also Ihara & Feldman [3] for a mathematical formulation of cultural niche construction). Social selection pressures derive from the fact that all human societies have an organization, or order, constituted by a series of overlapping, hierarchical role-structures [4–6] (see also Runciman [7] for a different but compatible view of social selection). These structures are defined by expectations of behaviour for role holders, expectations that are socially negotiated in a process we consider social selection [8]. Cultural selection pressures derive from the fact that human culture is a series of overlapping, nested sets of meaningful ideas [9] often referred to as symbolic or meaning systems. Note that 'meaningful ideas' is used as an anthropological technical term, referring to information that is shared, abstract, public (i.e. external to individuals) and either believed as truth by some percentage of the referent population or else closely associated with other ideas so believed [8,10] (see also [9,11–13]). Such ideas are expressed and learned behaviourally, yet internalized in individual minds [14,15]. Under cultural selection, ideas that an individual already has internalized influence his/her broadcasting, reception or internalization of subsequent ideas to which she/he is exposed [8] (see also [16–21]). Thus, human social niche construction occurs when social precedents feedback to change shared expectations of roles [8]. Human cultural niche construction occurs when belief

*Author for correspondence (melissa.brown@stanford.edu).
†M.J.B. and M.L. contributed equally to this manuscript.

One contribution of 13 to a Theme Issue 'Human niche construction'.

or disbelief influences whether particular ideas are accepted as meaningful (believed or associated with belief) in a population [8] (see also [1,3,22]).

We focus on the interaction of society (role-structures) and culture (ideas) and the potential for their distinct dynamics to reshape the cultural niche (see also [3,8,23–25]). Demographic and ethnographic data document a change in marriage practices in Taiwan during the early twentieth century, from a plurality of ways to select a mate to dominance of one form. Here, we present a formal model exploring the interaction of cultural ideas (represented by moral beliefs about marriage) and social structure (represented by an ability to pay brideprice), the phenotypic expression of this interaction in mate preferences (as represented by the actual marriage form practised), and the niche-constructing feedback to the content of the population ideational pool or cultural niche. Unlike Lansing & Fox's discussion [26] of the complex set of ideas in the Balinese water temples' ritual calendar, we focus on two specific cultural ideas in order to explore some of the nuanced interactions between cultural ideas and social structure.

2. DATA ON MARRIAGE CHANGE IN TAIWAN, 1906–1945

(a) *Marriage forms*

In rural Danei Township and Jibeishua village (in Dongshan Township) in Taiwan's southwestern county of Tainan (figure 1), frequencies of marriage forms changed between 1906 and 1945, both among the ethnic Han (Chinese) majority and the plains Aborigine (Austronesian) minority [27–29]. Although Han in Taiwan practised a range of marriage forms [27,30,31], there were primarily two forms of marriage in Danei and Jibeishua at the beginning of the twentieth century [28,32]. Virilocal 'major' marriage (嫁娶, lit. for a woman to leave her natal household as a man's wife)—where a young woman, after puberty, was transferred from her father's household to her husband's—was the Han cultural ideal, and it was common among both Han and plains Aborigines [27–29]. The cost of such a marriage—brideprice, feasting and fees for the go-between—was significant for the groom's family and was not offset by the dowry provided by the bride's family. The brideprice alone was often equivalent to a year's income for a farm family and could require 10–15 years of saving to accumulate [30]. (Note: In China and Taiwan studies, unlike African studies, 'brideprice' is the standard and appropriate translation for 聘金, not 'bridewealth', because the cash and gifts included in brideprice were culturally viewed as buying a woman and all rights to her labour and children [30,33–35]. Additionally, virilocal major marriages and uxorilocal marriages are generally referred to as 'marriage forms' rather than just post-marital residence because the terms encompass related rituals and jural rights and duties as well as residence; moreover, they are frequently compared with other forms of marriage which are also virilocal).

Uxorilocal marriage (招赘 or 招女婿, lit. bringing in a son-in-law)—where an adult man moved into his wife's household—was a persistent minority of marriages, of variable frequency [27,28,30,32]. Uxorilocal marriage required no brideprice, feasting, fees or dowry, for Han or plains Aborigines. Moreover, the concept of uxorilocal marriage in Taiwan included a range of practices that elsewhere in the world would be treated as distinct marriage forms. According to Wolf & Huang [30], the most common version of uxorilocal marriage among the Han was where a son-in-law would agree to give his father-in-law's surname to one or more of his sons, and only those boys would have rights of property inheritance of their maternal grandfather's property. Ethnographic evidence suggests that the most common form of uxorilocal marriage among plains Aborigines in the villages of Toushe (in Danei Township), Jibeishua (in Dongshan Township) and Longtian (in Guantian City) was essentially a form of brideservice, where no surname changes would be made, no property inheritance rights would be granted, and after 10 years or so of working for his father-in-law, a son-in-law would move his wife and children out and establish his own household [28]. Such variation fits within a larger Han acceptance of a wide range of marital forms. Unlike Christian Europe, where there was a largely uniform marriage type (serial monogamy) but wide variation in form of inheritance, in Han China and Han diasporas, there was a largely uniform inheritance form (all brothers inherited equally) but families could contract virtually any form of marriage mutually agreed upon [28,30,33,36–38].

One of the best predictors of uxorilocal marriage was sibling composition [30,39–41]. Han women who reached age 15 with no brothers or only very young brothers living in their household were much more likely to marry uxorilocally than women with at least one living older brother. Generally, these women's natal families had at least minimal property or tenancy rights, which could be used to entice a Han man into an uxorilocal marriage. These trends also appear to hold for plains Aborigines, but plains Aborigine women with older living brothers might also marry uxorilocally [27–29]. Poverty affected mortality rates, and thus sibling composition, but so too did stochastic effects. Elderly women Brown interviewed frequently reported having lost a brother or a husband when an oxcart flipped over on him. Whether such accidents left a household without male labour was a stochastic effect, for it depended on the existing sibling composition as determined by the prior history of the household. Pandemics, war and natural disasters also yielded stochastic effects. For Han men, conditions of poverty, which meant they could not pay a brideprice, caused, for example, by having five or more living brothers, or one or more parents deceased by the time a man reached marriageable age, best predicted whether he would marry uxorilocally. Among plains Aborigine men, the correlation with poverty appears to be less strong. (Note: Wolf used quantitative data to assess these correlations for a northern Taiwanese Han township; Brown used qualitative data from in-depth interviews in three southwestern plains Aborigines villages, discussed further below.)

Han viewed uxorilocal marriage as shameful; thus Han men who resorted to this form of marriage were

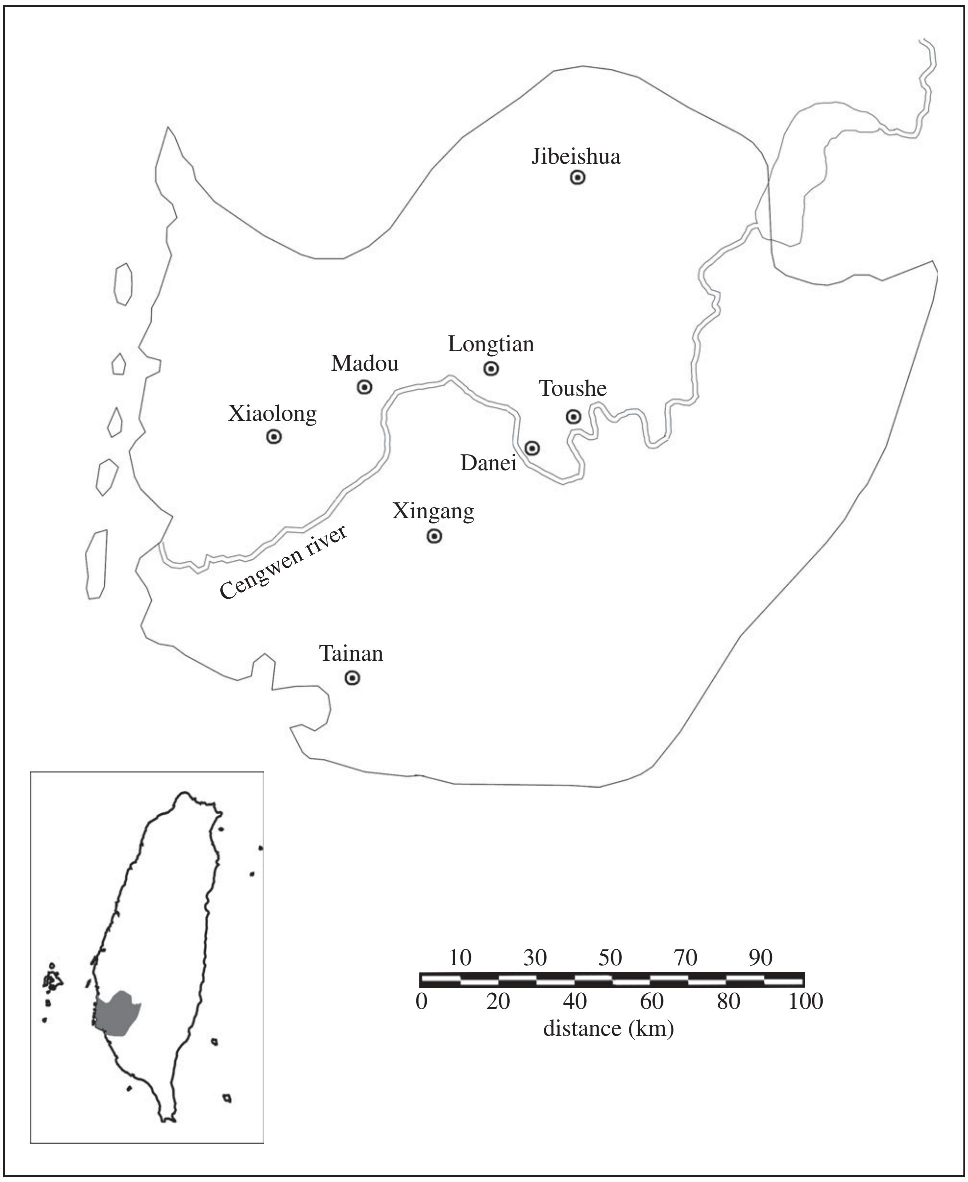

Figure 1. Map of Tainan County, Taiwan.

often viewed with suspicion by their in-laws and the local community [29,30,40]. By contrast, because uxorilocal marriage among plains Aborigines in the early twentieth century has generally been viewed as a holdover from seventeenth century matriliny (e.g. [27,28,42]), its 'traditional status' for Aborigines has led to the expectation 'that the factors that weaken uxorilocal marriage among the Han, especially the denigrated status of the in-marrying son-in-law and even the lack of trust in the relations of son-in-law to parents-in-law would be diminished among the plains [A]borigines' [29]. Further expectations that divorce rates for the uxorilocally married would be lower among plains Aborigines than among Han were not realized [29]. However, late nineteenth century European missionary reports that marriage was lax among plains Aborigines and divorce common—presumably also derived from matriliny—preclude the conclusion that uxorilocal marriages were not 'culturally honoured' [29].

Ethnographic research in the plains Aborigine villages of Toushe (Danei Township), Jibeishua (Dongshan Township) and Longtian (Guantian City), all in Tainan County, suggests that plains Aborigine residents there may have viewed uxorilocal marriage more neutrally than the Han. Some 79 elderly villagers (surviving, mentally capable villagers, aged 60 and older, interviewed in 1991–1992) who had been considered plains Aborigines in their youth reported on a total of 85 marriages in their parents' and grandparents' generation (which occurred roughly 1900–1920): 40 per cent of the 18 Longtian marriages were uxorilocal, 44 per cent of the 44 Jibeishua marriages and 70 per cent of the Toushe marriages [28]. These same villagers reported lower rates of uxorilocal marriage for their own generation (which occurred roughly 1925–1940): 35 per cent of the 20 Longtian marriages were uxorilocal, 31 per cent of the 35 Jibeishua marriages and 23 per cent of the 44 Toushe marriages [28]. Brown found that these 'plains Aborigine' villagers demonstrated no shame or reluctance in speaking of their own, their parents' or their grandparents' uxorilocal marriages. Nor did their reports describe maltreatment of uxorilocally married men within their community. The only uxorilocally married Han man who spoke ill of his plains Aborigine in-laws (who did not give him any property) confessed to not having honoured the terms of the marriage agreement by refusing to give any of his sons his father-in-law's surname. Given the sharp contrast of shame, reluctance and reports of discrimination about uxorilocal marriages in the ethnographic interviews in Han areas of Taiwan and China by Brown (during field research in 1991–1992, 1994, 1996, 2002 and 2009) and other anthropologists (e.g. [40]), the consistently neutral tenor of these responses provides strong, qualitative evidence that, in the early twentieth century, uxorilocal marriages did not hold the same stigma for plains Aborigines in these villages as they did for Han.

(b) *Ethnic relations*

The Hoklo variety of Han were the ethnic majority of Taiwan and Danei Township, but plains Aborigines constituted a numerical majority of Toushe village (in Danei Township) and Jibeishua village (in nearby Dongshan township) [28,32]. By the beginning of Japanese colonial rule (1895), ethnic relations between Han and plains Aborigines were peaceful, and plains Aborigines had adopted (Hoklo) Han language and many Han customs [28]. Plains Aborigines were stigmatized and identified primarily because they did not bind their daughters' feet, in contrast to the Han who lived in Danei and Jibeishua.

The ethnic border also served as a marital border. Some Han and plains Aborigines did marry, but such marriages were mostly regarded as shameful—poor Han men marrying uxorilocally to plains Aborigine women, or poor Han widows remarrying virilocally to plains Aborigine men. According to one elderly Jibeishua man, interviewed in 1992,

> The women [of his parents' and grandparents' generation] were all fierce. The men of surrounding villages [who were Han] did not want to marry them; they [the Han men] called them [Jibeishua women] *hoan-a-pho* [savage biddies], so the [Jibeishua] village men had to marry them [28].

In other words, Han would not arrange virilocal marriages for their sons with women stigmatized as 'savages'. Similarly, Han would generally not marry their daughters to plains Aborigine men as first-time brides (i.e. young women marrying for the first time). (Note that multiple marriages occurred via the practice of women remarrying following widowhood or divorce, which was common among both Han and plains Aborigines despite Han disapprobation (see [29,30]). Polygyny was accepted but relatively rare in China and Taiwan, as documented by the low frequency of concubine marriages in our database; see also [43].)

Plains Aborigines were poorer on average than Han in Tainan County [28,44]. However, plains Aborigines were economically better off in Jibeishua than Danei, owing to agricultural conditions. Danei was partly rich flood plains with paddy agriculture, dominated by Han, and partly foothills with limited irrigation, where most of the plains Aborigine minority lived. Jibeishua was on the Jianan plain, surrounded by paddy fields.

(c) *Economic development*

The Japanese colonial government (which ruled Taiwan 1895–1945) invested heavily in developing Taiwan between 1895 and 1930 [28,45] (see also [46,47]), constructing roads, bridges, a railroad system, hospitals, schools, sewage systems, dams, factories, sugar mills and more. Irrigation systems expanded the number of rice crops possible per year; in Jibeishua after 1925, when the Jianan irrigation system was in place, people could plant three rice crops per year. Public health measures effectively controlled plague, malaria and tuberculosis, reducing mortality rates across the board [48,49]. Although universal compulsory education was never achieved, most people, even in rural areas, had at least 2 years of primary education in Japanese. Many Taiwanese had the opportunity to attend middle school, making them suitable for entry-level employment in Japanese-run factories, businesses, government offices and banks. This economic and educational development resulted in non-elite Taiwanese (both Han and plains Aborigines) having more money. Thus, poor men were increasingly able to accumulate sufficient cash to pay a brideprice.

Such development produced fundamental changes in Taiwan's social niche. As defined above, a social niche is the sum of all social selection pressures, and social selection is the social negotiation process over expectations in the behaviour of role holders in hierarchically organized and networked role-structures. Economic development created new roles and new structures, for example, in factories, railroad systems and public health organizations. It also allowed many changes in continuing role-structures, such as the kinship system (for which marriage is an important means of recruitment). For example, Wolf [39] has documented quantitatively that the 'minor' form of virilocal marriage (where a family would adopt a young girl and raise her to be the wife of one of their sons) was common among Han in northern Taiwan at the beginning of the Japanese period but declined in frequency by 1925. Wolf uses qualitative, ethnographic evidence to attribute this decline to the ability of young people to buy themselves out of such marriages owing to the increased economic opportunities that came with colonial development (cf. Lim case study in Brown [45]). Here, young people used the resources available from modifications in the social niche to renegotiate the expected behaviour of sons and adopted daughters-in-law to such an extreme that they actually did away with the latter role entirely.

Also related to economic development, the Japanese colonial government, beginning in 1915, enforced a ban on the practice of footbinding. Elderly Han interviewed in 1991–1992 in Danei and Dongshan townships reported that Japanese police who supervised the unbinding of their mother's (or in one woman's case, her own feet) said the unbinding was for women to be able to work in the paddy fields. The footbinding ban was intended to expand female participation in agricultural labour, but it also unintentionally removed the ethnic boundary between plains Aborigines and Han and drove the subsequent assimilation of plains Aborigines in Toushe and

Jibeishua to a Han identity [28,45]. This removal shifted marriage patterns in Danei and Jibeishua by increasing the rates at which Han allowed their daughters to marry plains Aborigine men (as first-time brides) and at which Han brought in plains Aborigine brides for their sons [28]. In other words, the footbinding ban coincides with an overall decrease in uxorilocal marriage rates, both for plains Aborigines in relation to Han and for everyone overall (figure 2).

The resulting change in ethnic identity also had consequences for villagers' customs (practices) and cultural ideas [23,28,50]. By 1991, people practised customs largely indistinguishable from neighbouring villages that had always been considered Han (except for one part of their religious practices). Toushe and Jibeishua villagers whose identities changed from plains Aborigine to Hoklo Han also believed many more Han cultural ideas over time, although a lag in the adoption of ideas was still apparent [28,50]. Such evidence that the spread of cultural ideas in a population can follow the spread of an associated practice suggests that behaviour itself (phenotype) may be an important factor in cultural niche construction (i.e. changes in whether particular ideas are accepted as meaningful; cf. [8,23]).

The frequency of cultural ideas in the early-twentieth-century plains Aborigine population in these villages is unknown. The only evidence available is from retrospective ethnographic interviews from a surviving sample (e.g. [28]) or occasional historical claims, often by Western missionaries, about the cultural ideas of an entire village, county or even ethnic group (e.g. [29,51–53]). There is debate among Taiwan scholars about the degree to which southwestern plains Aborigines had adopted Han cultural ideas by 1900 (e.g. [28,29,42,50,54,55]).

(d) *Demographic data*

To monitor Taiwan's population, the colonial government developed a household registration system, in which every person had to register with the police as a member of one, and only one, household [30]. Information registered included name, age, sex, relation to the head of the household, marital status, and, in the early part of the Japanese period, 'class,' 'race' as inherited from one's biological father and (for females) whether feet were bound. Japanese-period registers for many localities have been computerized and archived. Some information in the original registers is not available in the public-use database, affecting some potential analyses. For example, all names have been replaced by identification numbers, which means that quantitative assessment of surname changes is not possible. Each locality database contains the above information for every single person alive between 1906 and 1945 who resided in that locality for at least 1 day. In other words, the people represented in the database for each locality (village, township, small city and urban neighbourhood) are the entire population for that 40 year period, not merely a sample.

The entire population, so defined, includes migrant households as well as long-term residents. Taiwan's

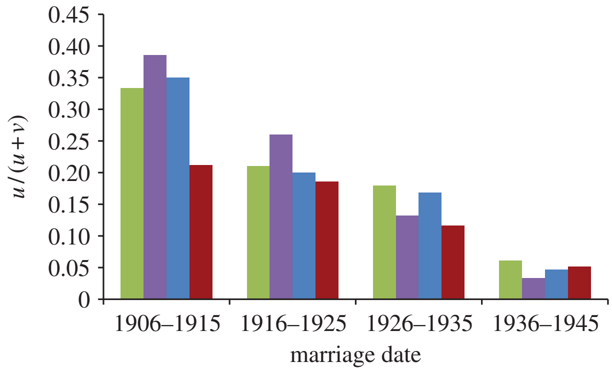

Figure 2. Proportion of uxorilocal marriages for Aborigine and Han women from Danei and Aborigine women from Jibeishua, by 10 year marriage cohorts. Green bars, Jibeishua Aborigines; violet bars, Toushe Aborigines; blue bars, Danei Aborigines; red bars, Danei Han. Note: Toushe Aborigines are a subset of the Danei Aborigine population.

population during the colonial period was extremely mobile, but the Japanese colonial government took measures to reduce the impact of such mobility on the household registers. Most importantly for our purposes, household registers reflect Taiwanese concepts of family (家), not merely residence. Individuals could be registered in their family's household but physically resident elsewhere. If individuals reported that they would be gone from the locality for a period of time, for example, for work, the local police merely added a pasted-on rice-paper strip to the comments section of their permanent household register indicating the sojourn. (They also had to register with the police in the locality to which they were going, but registered as sojourners, not as permanent residents.) Any marriages or other events that occurred during this period would be recorded on the permanent household register page in their home locality. There were relatively few sojourners in Danei and Jibeshua, since these localities include no major urban centres. In our analyses, we have excluded sojourners from consideration. Thus, only migrations that included the entire household are included in our effective populations.

The Danei and Jibeishua databases (recording information on 21 151 and 3268 people, respectively) provide the following information for every marriage that occurred between 1906 and 1945: date, form (uxorilocal or virilocal), first- or high-order marriage (indicating serial remarriage), community address of post-marital household (which allows us to identify residence in Toushe village within the larger Danei Township database). The databases also provide detailed information on spouses including, in many cases, their natal households.

In our analyses, we only examine first marriages for two reasons. First, we want to be able to compare our results to previously published studies of the Taiwan household registers, which focus on first marriages (e.g. [27,29–31,38,39,40,56]). Second, remarriages occurred with different social expectations, under different economic conditions, and with different cultural views from first marriages. Moreover, first marriage form does not necessarily predict remarriage form. Wolf & Huang [30] suggest that remarriages have a higher frequency of uxorilocal marriages than first marriages. For example, a virilocally married woman whose husband died young (especially if he left young sons and no brothers) was highly likely to marry uxorilocally, either arranged by her parents-in-law or herself, since there was likely to be both property and need of adult male labour.

We also focused on uxorilocal and virilocal major forms of marriage because other forms of marriage were relatively rare in these particular sites. For local women married from their natal homes in first marriages, occurring any time between 1906 and 1945, there were 2003 virilocal major marriages in all Danei Township, 374 uxorilocal marriages, 166 minor marriages (only nine of which included plains Aborigines) and 27 concubine marriages. In Jibeishua village, there were 342 virilocal major marriages, 99 uxorilocal marriages, 17 minor marriages (eight of which included plains Aborigines) and six concubine marriages. (Note: Concubine marriages were always to virilocally married men).

Here, we present uxorilocal marriage rates for women from the township of Danei and the villages of Toushe and Jibeishua between 1906 and 1945. We define the uxorilocal marriage rate, U, as the ratio $u/(u+v)$, where u is the number of first uxorilocal marriages among all the women from a particular village or township during a particular period of time, and v is the corresponding number of first virilocal (major) marriages. These data count women who were living in households in Danei or Jibeishua at the time when the woman either left her household to marry (virilocally) or had a husband brought in for her. Thus, we are counting the marriages of women from that locality at the time of marriage. Those whose first marriages contributed to the Toushe rate are women who were living in households in Toushe on their 15th birthday, generally the earliest age at which first marriages occurred (e.g. [30]), although plains Aborigine women tended to marry at later ages than Han women [29]. (Note: This qualification reduces the number of women in migrant households included in the Toushe figures.)

We calculate the marriage frequencies in terms of marital cohorts (e.g. figure 2) because this calculation captures period effects—larger historical factors that affected all marriages at a particular time, such as the 1915 footbinding ban. Note that no error range is indicated because the data are not a sample; rather, they represent the entire population of specified women. The first cohort shows the plains Aborigines with a clearly higher rate of uxorilocal marriage than Han. We do not know how these frequencies of the practice of uxorilocal marriage relate to cultural ideas. There follow two cohorts where the Aborigine rates drop and approach the Han rates, and finally a cohort that shows no significant difference between the Han and Aborigine rates. (A two-sample test of equality of proportions with continuity correction indicated that the Danei Aborigine and the Danei Han uxorilocal marriage proportions in the fourth cohort are the same.) There is a more-or-less steady decline in uxorilocal marriage in all groups over the colonial period to a low of about 5 per cent in the final cohort, but the decline in the Aborigine rates from the first to second cohort is strongest.

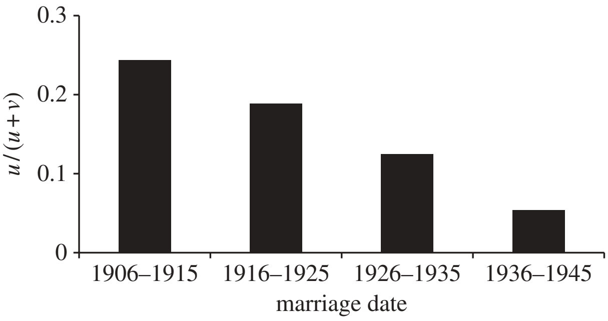

Figure 3. Rates of uxorilocal marriage for all women from Danei, by 10 year marriage cohorts.

We primarily use the data in figure 3 from Danei only, which combine the rates for Han and plains Aborigine women, to inform construction of a basic model of declining uxorilocal marriage rates, because this combination simplifies the mathematical calculations. (The marital-cohort rates in figure 3 can be understood as weighted averages of the Danei Han and Danei Aborigine rates presented in figure 2.) However, in the analysis, we do use data on Danei Han only (U_{H1}) from figure 2 to calculate the historical projections of changing beliefs.

3. MATHEMATICAL MODEL

Based on the qualitative and quantitative evidence summarized above, we identified the following key factors that might have affected uxorilocal marriage rates in Taiwan: a set of cultural ideas about the shamefulness of uxorilocal marriage (including association with son preferences), economic conditions affecting the cost of a virilocal marriage (especially the bride-price), and sibling composition (which is affected by both economic and stochastic effects on mortality rates). As discussed above, it is unknown—and unlikely to ever be known—what the frequency of cultural ideas regarding marriage was at the beginning of the Japanese colonial period in Taiwan. It is, however, clear that economic and public health conditions improved dramatically over the course of the colonial period, resulting in greater wealth in the population and lower mortality rates.

Given the importance of poverty and sibling composition in predicting the probability of uxorilocal marriages (e.g. [27,30]), and given evidence that practices can and do change before cultural ideas [28,50], the influence of cultural niche construction is not clear. In other words, it is not clear whether or how cultural ideas about marriage form must have changed before, during or even after the decline in uxorilocal marriage rates. Thus, we turn to a mathematical model to indicate the possible dynamics of cultural ideas, given the known changes in the social niche. In constructing the model, we allow for direct influence of cultural ideas and a population economic index. We also include an indirect representation of stochastic influences on sibling composition.

(a) *Transmission of cultural ideas*

We suppose that every person in the locality has a cultural idea about the morality of virilocal and uxorilocal marriages, which affects the relative desirability of each form. Each person either has an idea (σ_1) that uxorilocal marriages are immoral and thus undesirable or an idea (σ_0) that uxorilocal and virilocal marriages are equally moral and desirable. In other words, people with σ_0 are neutral; they have no clear preference between the two forms of marriage. An interesting consequence of the empirically based conceptualization of these cultural ideas as a preference and neutral idea is that under certain conditions, discussed below in 'calculating the uxorilocal marriage rate', σ_1 is dominant over σ_0. (For any individual, σ is assumed to be independent of monetary wealth.) We define x as the proportion of people who have $\sigma = \sigma_0$ at a given time in a particular population, and $1 - x$ is the proportion of people with $\sigma = \sigma_1$.

Our model includes horizontal transmission of σ [16]. We allow for the possibility that the empirical decline in uxorilocal marriage was driven by a change in beliefs. The rapidity of this decline (less than a generation), especially for plains Aborigines, means that cultural influence must have come horizontally rather than vertically. Moreover, once marriage form was already changing, individuals may well have been influenced in their opinion of marriage forms practised by their own and adjacent cohorts. Consequently, our model assumes that vertical transmission does not produce a change in the value of x between the parental and offspring generations (it is unbiased) and also that whether a person believes uxorilocal marriages are immoral (σ_1) or neutral (σ_0) is affected by the beliefs of others within the same biological generation. (Note: The model assumes that cultural selection operates by ideas directly influencing each other, but empirically we would expect individuals' ideas to be influenced both by the expressed ideas of their peers and observations of the outcomes (e.g. divorce) of actual marriages (phenotype) in the adjacent cohorts—siblings, cousins, neighbours and classmates.) For simplicity, we assume that both vertical and horizontal transmissions of ideas are gender-blind, so that the system quickly reaches a state where x is the same in both genders.

(b) *Population economic index*

We introduce W, a population-level economic index. Given that colonial Taiwan was economically highly stratified, we conceptualize W not as wealth in general but as the proportion of individuals in the population that had sufficient wealth to pay a brideprice. This view of W makes the model slightly more realistic because the range of variation in brideprice was considerably less than the range of variation in overall wealth in the population [30].

W ranges between 0 and 1. When $W = 0$, poverty is so great that no one can afford to pay brideprice and everyone marries uxorilocally. When $W = 1$, societal wealth is sufficiently high that everyone has enough money to pay a brideprice and, thus, everyone can marry according to his/her cultural beliefs. Since one of the two beliefs in the model is neutral, having enough money for a brideprice will not automatically make a person with σ_0 marry virilocally. Taiwan's overall wealth increased during the colonial period, so we would say that W increased. Thus, in contrast to Shennan [57], we consider an industrializing context in which access to resources increases over time and for a larger percentage of the population.

We recognize that using a population-level economic index is not ideal. We use a population-level index because, first, although we do not have village- or township-wide, individual-level data on wealth, we do have reliable qualitative evidence of the population-wide increase in wealth. Second, the poor, rural character of Danei Township and Jibeishua Village suggests that the within-population variation in the ability to pay brideprice can be approximated by the proportion W. We are not assuming that the level of brideprice in this poor rural area of Taiwan would not itself increase with increasing population wealth. Rather, based on Brown's ethnographic interviewing about the arrangement of marriage in different generations and Wolf's [39] ethnographic evidence discussed above about young people buying themselves out of minor marriages, we assume that, with economic development, more poor men in Danei and Jibeishua had the option of sojourning in an industrial centre and thereby accumulating the needed wealth to return to their rural homes with enough cash for a brideprice. As more men tapped into the industrializing economy outside of Danei, W, the proportion able to pay a brideprice, increased.

(c) *Indirect effects on σ_1*

The model includes a constant parameter, s, which ranges between 0 and 1, and measures the degree to which the cultural belief σ_1 influences a person's marriage practice. We include this parameter in the model because empirical evidence suggests that, despite viewing uxorilocal marriage as shameful, Han arranged uxorilocal marriages for their daughters if they had no sons. When s is low, the influence of σ_1 is low because the cultural idea is swamped by mitigating effects. As discussed above, sibling composition is a reliable predictor of uxorilocal marriages, and sibling composition is strongly correlated with mortality rates, which are in turn affected by both poverty and stochastic occurrences. The parameter s is intended to capture the stochastic effects on sibling composition, such as farm accidents. Stochastic events that could affect sibling composition and make s low include the 1918 influenza pandemic and colonial conscription of men as coolie labour for the Japanese Imperial Army during World War II (table 1). (Plains Aborigines and Han in Danei and Jibeishua were affected by both of these events.) Decreasing s increases the proportions of uxorilocal marriages for people with σ_1 (rows 2 and 3 in table 2). When s is high, the cultural idea has a strong influence on practice because mitigating effects have little significance (they are minor events, or fewer in number). For example, although hurricanes occur in Taiwan, there

Table 1. List of variables and symbols.

name	definition
σ	cultural idea held by individual regarding morality of uxorilocal and virilocal marriage forms, which affects the relative desirability of each form. Takes one of two values.
σ_0	idea that uxorilocal and viriilocal marriages are equally moral and desirable.
σ_1	idea that uxorilocal marriages are immoral and undesirable.
x	proportion of individuals in the population with $\sigma = \sigma_0$ at a given time.
W	a population-level economic index. The proportion of individuals in the population having sufficient wealth to pay a brideprice. Varies between 0 and 1.
s	degree of influence of σ_1 on a person's marriage practice, due to stochastic mitigating effects. Varies between 0 and 1.
U	total effective proportion of uxorilocal marriages in the population. $U = x^2(1-\frac{1}{2}W) + 2x(1-x)(1-\frac{1}{2}W[1+s]) + (1-x)^2(1-\frac{1}{2}W[2-(1-s)^2])$
H	horizontal transmission. The difference between the proportion of people switching to σ_0 and the proportion of people switching to σ_1. $H \equiv H_{10} - H_{01}$. Ranges between −1 and 1.

Table 2. The probability of uxorilocal marriage by pairing type.

	marriage pairing type	frequency of these marriage pairings	Pr[uxorilocal marriage]
1.	$\sigma_0 \times \sigma_0$	x^2	$1 - \frac{1}{2}W$
2.	$\sigma_0 \times \sigma_1$	$2x(1-x)$	$1 - \frac{1}{2}W(1+s)$
3.	$\sigma_1 \times \sigma_1$	$(1-x)^2$	$1 - \frac{1}{2}W[2-(1-s)^2]$

was no mention of hurricane-related deaths in ethnographic interviews.

Because s is a constant—it is the same for everyone in the population—we operationalize it as saying that people are subject to the same risk of stochastic events that might affect their sibling composition. For example, people were at the same risk that a male in their household would die from the flu pandemic, would die because an oxcart laden with sugarcane would overturn or would be pressed into labour service for the army. This assumption, entailed in making s a constant, does not take into account the influence of poverty or household occupation in the probability that such events affect any particular household. We make this simplification for tractability of the model, but we also suggest that economic influences on the impacts of these events can be conceptualized as being incorporated into the economic index, W.

(d) *Calculating the uxorilocal marriage rate*

In table 2, we present the probabilities that hypothetical couples with specified cultural ideas (σ_0 or σ_1) will marry uxorilocally, assuming pairing is random with regard to σ in order to keep the model as simple as possible. In row 1, we see that the frequency of couples both having σ_0 is x^2. Empirically, mating is probably not entirely random with regard to σ. However, the ethnographic evidence discussed above of the potential effects of poverty and sibling composition on marriage forms does suggest some randomness of mating with respect to σ, since poverty or sibling composition could lead people with a strong personal belief in the cultural idea σ_1, that uxorilocal marriages are shameful, to marry uxorilocally. If everyone in the population is wealthy enough to afford brideprice and thus to marry as they like (i.e. $W = 1$), then the probability that a $\sigma_0 \times \sigma_0$ couple will marry uxorilocally is $\frac{1}{2}$, because both individuals are neutral about marriage form. (Here, we ignore the possibility that a desire to save the brideprice for other uses might bias the frequency towards uxorilocal marriages.) Hence, from the third column of table 2, Pr[uxorilocal marriage $\mid \sigma_0 \times \sigma_0] = 1 - \frac{1}{2}W$.

In row 3 of table 2, the probability that a $\sigma_1 \times \sigma_1$ couple will nevertheless marry uxorilocally is strongly influenced by the direct effects of wealth (the proportion of people who can afford a brideprice) and the indirect effects of s on σ_1: Pr[uxorilocal marriage $\mid \sigma_1 \times \sigma_1] = 1 - \frac{1}{2}W[2-(1-s)^2]$. If the population is so poor that no one can afford a brideprice (i.e. $W = 0$), then 100 per cent of these couples will marry uxorilocally, despite their cultural belief σ_1. If, at the other extreme, the population is wealthy enough that everyone can marry according to preference (i.e. $W = 1$), then the rate at which they marry uxorilocally will be determined by s, which affects both individuals in the couple. If the effect of σ_1 is negligible ($s = 0$) and if everyone can afford brideprice ($W = 1$), uxorilocal marriage occurs randomly (Pr[uxorilocal marriage $\mid \sigma_1 \times \sigma_1$ and $W = 1$ and $s = 0] = \frac{1}{2}$). There is no influence from σ_1, leaving σ_0 as the only cultural belief, and since σ_0 is neutral with regard to marriage form, its influence is to push the frequency of uxorilocal marriages towards neutrality (i.e. $\frac{1}{2}$). If the effect of σ_1 is maximized ($s = 1$) and if everyone can afford brideprice ($W = 1$), the probability of uxorilocal marriage is 0 because couples are able to follow their beliefs and $\sigma_1 \times \sigma_1$ couples have a strong preference against uxorilocal marriage.

In row 2, the probability that a $\sigma_0 \times \sigma_1$ couple will marry uxorilocally is directly affected by societal wealth (W) and also indirectly affected by s. If the population is so poor that no one can afford a brideprice (i.e. $W = 0$), then 100 per cent of these couples will marry uxorilocally, despite the cultural belief σ_1 of one of the couple. If, at the other extreme, the population is wealthy enough that everyone can marry according to preference (i.e. $W = 1$), then the rate at which they marry uxorilocally will be determined by

s, which affects only one individual in the couple (since only one has σ_1). If the effect of σ_1 is negligible ($s = 0$), then, even if everyone can afford brideprice ($W = 1$), uxorilocal marriage occurs randomly (Pr[uxorilocal marriage | $\sigma_0 \times \sigma_0$ and $W = 1$ and $s = 0] = \frac{1}{2}$) because the other member of the couple is neutral with respect to marriage form. If the effect of σ_1 is maximized ($s = 1$) and if everyone can afford brideprice ($W = 1$), the probability of uxorilocal marriage is 0 because couples are able to follow their beliefs and one member of the couple has a strong preference against uxorilocal marriage while the other is neutral (hence the one with the strong belief will hold sway). In other words, σ_1 is dominant over σ_0. When $s = 1$, the proportion of uxorilocal marriages for $\sigma_1 \times \sigma_1$ and $\sigma_0 \times \sigma_1$ couples is at its lowest value of $1 - W$.

We can use table 2 to calculate U, the total effective proportion of uxorilocal marriages in the population:

$$U = x^2\left(1 - \tfrac{1}{2}W\right) + 2x(1-x)\left(1 - \tfrac{1}{2}W[1+s]\right) + (1-x)^2\left(1 - \tfrac{1}{2}W[2-(1-s)^2]\right). \tag{3.1}$$

In other words, the number of expected uxorilocal marriages in the population is the sum, for each of the random pairings, of the frequency of the pairing multiplied by the probability that pairing will result in an uxorilocal marriage.

(e) *Horizontal transmission*

Couples in cohort t match up, marry and transmit beliefs to cohort $t + 1$. We refer to couples in different cohorts, rather than generations, because the passage of time between the cohorts is generally not sufficient for biological reproduction and we have assumed that vertical transmission is unbiased. Horizontal transmission of cultural ideas can occur in a variety of ways. For example, a person with idea σ_0 in cohort $t + 1$ can receive a broadcast expression from a person with idea σ_1 and change his/her idea to σ_1. Alternately, a person with belief σ_0 in cohort $t + 1$ can observe a marriage as practised by a couple in cohort t and change his/her belief to σ_1. The probability of a change from σ_0 to σ_1 is H_{01}, and the probability for a change from σ_1 to σ_0 is H_{10}. Horizontal transmission influences cultural selection. It is viewed as different from the more subtle effects of cultural niche construction, where a person with idea σ_0 in cohort $t + 1$ receives a broadcast expression from a person with idea σ_1 and this reception changes his/her perception of which idea is generally believed and thus meaningful in the larger population.

At the conclusion of this horizontal transmission process, the proportion of people with belief σ_0 is equal to

$$x_{\text{next}} = x + Hx(1-x), \tag{3.2}$$

where H is defined as the difference between the proportion of people switching to σ_0 and the proportion of people switching to σ_1 ($H \equiv H_{10} - H_{01}$). H ranges between -1 and 1. When everyone is switching to σ_1 ($H = -1$), the reduction in x is the greatest, and x decreases quadratically: $x_{\text{next}} = x^2$. When everyone is switching to σ_0 ($H = 1$), the increase in x is the greatest: $2x - x^2$.

4. SOCIAL MEDIATION OF THE EXPRESSION OF CULTURAL IDEAS

At the origins of cultural evolution modelling, Cavalli-Sforza & Feldman [58] made a simplification in the cultural transmission process for modelling facility (which did not interfere with their goal of countering Arthur Jensen's racist claims by demonstrating that non-genetic effects could lead to the educational inequalities he cited as support, see also [59]). Although culture was defined as learned information, transmission was modelled more simply as the imitation of behaviour (the effects of parental phenotype directly on children's phenotype). The precedent of this simplification established an expectation for modelling cultural transmission that became standard in the field (e.g. [1,16,17].) (Note: Durham [60] did not make this simplification, but because he did not mathematically model the alternative cultural transmission process he proposed, modelling practices did not shift.)

This simplification implies a one-to-one correspondence between cultural information and human behaviour—in other words, an implication that once individuals acquire information they act on it. This highly unrealistic implication has contributed to wider social science scepticism of cultural evolution modelling, for anthropologists, sociologists, historians and other scholars have long recognized that individuals often have ideas in their heads that they are not interested in or able to implement in practice (cf. [10,14,18,23,60,61]; e.g. [30,39,40,62]). The general model we present here moves away from that simplification towards realism by treating cultural ideas (which are learned information stored in the mind) as analogous to genotype: mediated by external, 'environmental' factors—here, factors in the social niche—which affect the expression of these ideas in behaviour (phenotype).

Two sample theoretical scenarios explore how the frequency of cultural ideas (x) can be environmentally mediated by societal wealth (W) and stochastic events (s) to affect the frequency of uxorilocal marriage in practice (U). (In §5, we apply this general model to the Danei data.) In both scenarios, $x_0 = 0.3$, $s = 0.7$ and $H = -1$. We set the initial frequency of σ_0 in the population at $x_0 = 0.3$, which is approximately the frequency of uxorilocal marriage (U) in the overall Danei population at the beginning of the Japanese period (figure 3). In other words, we assume that any disjuncture between behaviour and belief prior to cohort 1 (married between 1906 and 1915) was accounted for by s—for example, among Han who viewed uxorilocal marriage as shameful but arranged uxorilocal marriages when they had no sons—but that cultural ideas have since come into one-to-one correspondence with behaviour (cf. [28,50]). We set the initial values of belief and behaviour roughly equal to show that incorporating relatively simple economic (W) and stochastic (s) effects yields the more realistic result of a disjuncture of belief and behaviour, even with initial values working against this outcome. We choose a negative value for H because, based on ethnographic research [28,50], we expect x to decrease over time, albeit after the change in practice. We set the influence of cultural belief σ_1 as mitigated by stochastic events, s, at an intermediate value in its empirically derived range (see appendix and table 3).

W, the population economic index, differs between the two scenarios. In scenario 1, W is held constant at 0.8, a relatively wealthy level at which 80 per cent of people can afford brideprice. In scenario 2, we allow W to change over time ($W = 1 - ke^{-at}$, a standard way of expressing exponential decay, where $k = 0.3$ and $a = 0.5$), in order to introduce more realism into the model as we know that economic development increased the wealth of Taiwanese society over the course of the colonial period. Thus, in scenario 2, W starts at 0.7 and increases exponentially up to 1, yielding an average value of W close to 0.8 (very close to the value in scenario 1).

We use equations (3.1) and (3.2) to calculate the proportion of σ_0 in cohort $t + 1$, given the proportion in cohort t. Since $H \leq 0$ in both scenarios, x decreases towards 0, and U tends to the proportion of uxorilocal marriage among $\sigma_1 \times \sigma_1$ couples. (If we were to set H greater than zero, x would increase towards 1, and U would tend to the proportion of uxorilocal marriage among $\sigma_0 \times \sigma_0$ couples.) In figure 4, we plot x and U for cohorts 1 through 4 in these two theoretical scenarios. In both scenarios, x (plotted in purple) is the same (since H is the same). In scenario 1, U (plotted in green) tends to $1 - \frac{1}{2}\ W\ [2 - (1-s)^2] = 0.236$. In scenario 2, U (plotted in blue) tends asymptotically to $\frac{1}{2}\ (1-s)^2 = 0.045$, and it spans a greater range of values than in scenario 1.

Figure 4 shows the disjuncture between the frequency of a custom, in this case uxorilocal marriage (U), and the frequency (x) of an associated belief (σ_0) when economic (W) and indirect, stochastic effects (s) are introduced. In scenario 1, where U (plotted in green) and x (plotted in purple) are initially equal and W is constant at a relatively wealthy level, the divergence is clear. Moreover, the divergence is stable, since U approaches 24 per cent. In scenario 2, where W changes over time, U tracks the decline in x over time, but there is a significant time lag. Even at the (unrealistic) extreme of $x = 0$ and $W = 1$ in the fourth cohort, U is still over 10 per cent. Thus, marriage form frequency gives little guidance on underlying cultural beliefs about marriage (mating preferences). The results of these theoretical scenarios—which are in agreement with the observed persistence of uxorilocal marriages even in the apparent absence of supporting beliefs—suggest the presence of an additional crucial factor to the construction of human cultural niches. We identify this factor as society, in which we include political economy (cf. [7,8]).

5. PROJECTIONS OF THE CULTURAL NICHE

By linking our general mathematical model (from the previous section) to the empirical data from Danei, here, we estimate the model's parameters and produce five possible projections of the historical changes behind the decline in uxorilocal marriage rates. These projections allow us to assess the relative effects of each of the parameters (x, s and W) on the uxorilocal marriage rate (U) and also to explore how the cultural niche is constructed—in other words, whether and how the content of the population ideational pool changes.

(a) *Linking the model and the empirical data*

We denote marriage cohorts in the time periods 1906–1915, 1916–1925, 1926–1935 and 1936–1945 by subscripts 1 through 4, respectively. Accordingly, U_1 through U_4 refer to the empirical Danei-wide uxorilocal marriage rates during these four time periods, as documented in figure 3. (Thus, U_4 has the lowest value.) Similarly, U_{H1} refers to the uxorilocal marriage rate between 1906 and 1915 for a subsection of the Danei population: Danei Han women who lived and married outside of Toushe. (This rate is documented in figure 2 by the red column in the 1906–1915 range.) These rates are the empirical data incorporated into the model. We denote the population economic indices in the time periods 1906–1915, 1916–1925, 1926–1935 and 1936–1945 by W_1 to W_4, the prevalence of σ_0 for the same time periods by x_1 to x_4, and the prevalence of σ_0 in 1906–1915 for the Danei Han outside of Toushe by x_{H1}.

We make several assumptions to simplify the model. The first two are empirically derived. First, we assume that $x_{H1} = 0$, given ethnographic accounts of Han moral disapproval of uxorilocal marriage (discussed above [30,40]). (Note: we do not make assumptions about the value of x for the plains Aborigine population because of the existing debate, discussed above, over whether Aborigine cultural ideas had changed (e.g. [28,29,42,44,54,55]). Second, we assume that, for the 1936–1945 period, any remaining $\sigma_0 \times \sigma_0$ couples marry uxorilocally about as often as they marry virilocally. In other words, given historical evidence of Taiwan's increasing economic development over the colonial period, we assume that in time period 4, there is no economic pressure to marry in either fashion (i.e. $W_4 = 1$, the maximum possible value of the population economic index). This assumption parallels Wolf's [39] findings, discussed above, that young people were able to buy themselves out of minor marriages by the end of the colonial period. Furthermore, we assume that s and H remain constant between 1906 and 1945, that W is constant for each cohort (since it represents the proportion of people in the cohort who can afford brideprice) but variable between time periods, and that U and x can vary between time periods of the population.

Finally, we assume that equation (3.1) holds across subsections of the population and across time, despite the evidence that before 1915 the marriage market was segregated in the township of Danei. Demographic data do show that, before 1915, uxorilocal marriage rates were different for the Aborigine and Han populations (figure 2) and each ethnic group was largely

Table 3. Five projections of the historical events behind the empirical values of U_1, U_2, U_3, U_4 and U_{H1} in figures 2 and 3.

projection	1	2	3	4	5
s	0.673	0.755	0.837	0.918	1.000
H	−0.872	−0.157	0.00337	0.0636	0.0691
W_1	0.833	0.813	0.799	0.791	0.788
W_2	0.865	0.866	0.857	0.851	0.849
W_3	0.926	0.929	0.925	0.921	0.920
W_4	1.000	1.000	1.000	1.000	1.000
x_1	0.150	0.168	0.195	0.233	0.284
x_2	0.0390	0.146	0.195	0.244	0.298
x_3	0.00634	0.126	0.196	0.256	0.313
x_4	0.000848	0.109	0.196	0.268	0.328

endogamous (i.e. most Han married other Han, and most Aborigines married other Aborigines; see [29]). Moreover, ethnographic reports about the social treatment of uxorilocally married men also suggest that Han individuals were more likely than Aborigine individuals to have $\sigma = \sigma_1$. However, in order to simplify the model, we suppose that the marriage market was random with respect to σ, so that equation (3.1) holds for the Danei population between 1906 and 1915.

(b) *Calculating the projections*

In order to calculate the historical projections, we begin by obtaining the range of s. Given a particular value of s, we can calculate numerical values for H, x_i and W_i that represent one projection behind the empirical values of U_1, U_2, U_3, U_4 and U_{H1}. We find that

$$1 - \sqrt{2U_4} < s \leq 1. \tag{5.1}$$

Having found the range, we start with s just above the lower bound of its range, $s = 0.673$, then compute x_4, W_1 and x_1 (see appendix equations (A 3), (A 4), (A 5), (A 6) and (A 7)):

$$x_4 = 1 - \frac{1 - \sqrt{2U_4}}{s}, \tag{5.2}$$

$$W_1 = \frac{2(1 - U_{H1})}{1 + s(2 - s)} \tag{5.3}$$

and $$x_1 = 1 - \frac{1 - \sqrt{2(((U_1 - 1)/W_1) + 1)}}{s}. \tag{5.4}$$

Now we consider how horizontal transmission (H) affects the frequency of cultural beliefs (x). Equation (3.2) describes the transitions between cohorts 1 and 2, cohorts 2 and 3 and cohorts 3 and 4. Thus, we obtain the following identity (see appendix equation (A 10)):

$$\begin{aligned} x_4 = x_1[&1 - 3H(1 - x_1) + 3H^2(1 - x_1)(1 - 2x_1) \\ &- H^3(1 - x_1)(1 - 9x_1 - 9x_1^2) + 5H^4x_1(1 - x_1)^2 \\ &+ H^5x_1(1 - x_1)^2(1 - 8x_1 + 8x_1^2) + 2H^6x_1^2 \\ &\times (1 - 2x_1)(1 - x_1)^3 + H^7x_1^3(1 - x_1)^4]. \end{aligned} \tag{5.5}$$

This identity allows us to calculate H, given x_1 and x_4, which in turn allows us to use equation (3.2) to calculate x_2 and x_3:

$$x_2 = x_1 + Hx_1(1 - x_1) \tag{5.6}$$

and

$$x_3 = x_2 + Hx_2(1 - x_2). \tag{5.7}$$

Once we have x_2 and x_3, we can use equation (3.1) to obtain W_2 and W_3:

$$W_2 = \frac{2(1 - U_2)}{1 + s(1 - x_2)(2 - s[1 - x_2])} \tag{5.8}$$

and

$$W_3 = \frac{2(1 - U_3)}{1 + s(1 - x_3)(2 - s[1 - x_3])}. \tag{5.9}$$

In sum, given $s = 0.673$, we have calculated numerical values for H, x_1, x_2, x_3, x_4, W_1, W_2 and W_3, which constitute projection 1 in table 3 and figure 5.

To calculate the remaining projections in table 3, we use $s = 1$, the upper limit of the parameter's range (in column 5), and choose the three values of s that divide its range into four equal segments. We then compute H, x_i and W_i for each of these values, using the process described above for $s = 0.673$. We incorporate the empirical data for U_i from figures 2 and 3 into the model. Using this method, equation (A 10) yields exactly one real value of H between −1 and 1 in each of the four additional projections. Results of these computations are presented as projections 2 to 5 in table 3 and figure 5.

(c) *Discussion: relative effects on marriage form and cultural belief*

The projections in table 3 allow us to assess the relative contributions of cultural and economic factors on marriage form (phenotype) because the five projections differ in the causal factors lowering the uxorilocal marriage rate (U). In projections 1 and 2, the drop is partly due to the increase in the proportion of people who can afford brideprice (W) and partly due to a decrease in the prevalence (x) of the cultural idea (σ_0) of neutrality towards uxorilocal marriage. In projection 3, the drop is caused chiefly by an increase in W, because the prevalence of σ_0 does not change very much. In projections 4 and 5, a rise in W explains

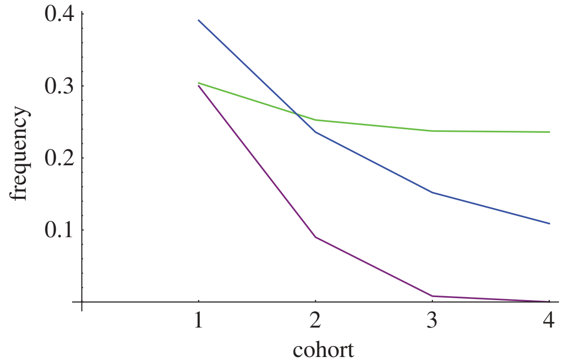

Figure 4. x and U for two theoretical scenarios (x in purple, U in green for scenario 1 where W is constant, U in blue for scenario 2 where W increases exponentially).

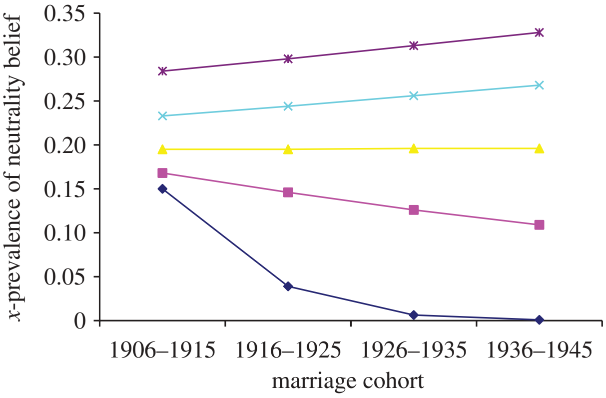

Figure 5. The frequency (x) of cultural belief σ_0 across cohorts for projections 1–5. Dark blue diamonds, projection 1; pink squares, projection 2; yellow triangles, projection 3; light blue crosses, projection 4; purple asterisks, projection 5.

the decrease in U, even though the prevalence of σ_0 slightly increases.

Figure 5 plots x_1, x_2, x_3 and x_4, the frequency (x) of the cultural belief (σ_0) in marriage cohort 1 (1906–1915), 2 (1916–1925), 3 (1926–1935) and 4 (1936–1945), respectively, for each of the five projections in table 3. Figures 2 and 3 demonstrated that U, the rate of uxorilocal marriages, declines across the same marriage cohorts depicted in figure 5. However, in figure 5, the frequency (x) of the cultural belief (σ_0) does not necessarily decline. In projections 4 and 5, the frequency of the belief (σ_0) in the neutrality of uxorilocal marriage actually rises ($x_4 > x_1$), albeit modestly. Projection 3 rises so imperceptibly that it could easily be mistaken for stationary ($x_4 = x_3 = 0.196 > x_2 = x_1 = 0.195$; table 3). Projections 1 and 2 do show declines in the frequency of this cultural belief, but they follow different trajectories. Projection 2 declines linearly, still leaving a frequency (x) of the belief (σ_0) of over 10 per cent in cohort 4, when the uxorilocal marriage rate (U) was already under 10 per cent (data in figure 3). Only projection 1 shows an exponential decrease in the frequency (x) of the belief (σ_0). However, this projection nears 0 in cohort 3, when the rate of uxorilocal marriage (U) was still over 10 per cent (data in figure 3). The clear conclusion is that there is no necessary correspondence between custom and belief, since it is possible for custom to diverge from belief, sometimes quite widely.

We expect the prevalence (x) of cultural belief σ_0 to have decreased over time because qualitative evidence (discussed above) suggests that, by the 1990s, many Han cultural ideas had become dominant in the former plains Aborigine communities of Toushe, Jibeishua and Longtian [28]. Consequently, the first two projections, where x decreases with time, meet our expectations better than the latter two, where x increases. That two of the projections lead to an increase in x, however, suggests that in the absence of quantitative empirical data on x, we cannot be certain of its prevalence and thus we cannot resolve the debate over the actual historical frequency of Han cultural ideas among plains Aborigines in Danei at the beginning of the colonial period. The model suggests the possibility that the prevalence was 0—i.e. that there was no belief in neutrality at all—at the beginning of the colonial period. However, the qualitative evidence, discussed above, regarding the lack of shame and discrimination attached to uxorilocal marriage in Toushe, Jibeishua and Longtian suggests that the cultural idea of neutrality existed, even if at low frequency. In those projections that meet our expectations, there is still a range of possible frequencies of the cultural idea, from near 0 to over 10 per cent. This range raises questions about the other influences on U in the model: W and s.

Table 3 shows that, within a single projection, a small change in the economic situation, represented by W, implies a larger change in culture (indicated by x). In other words, within any single projection, influences of the frequency (x) of cultural ideas on changes in the uxorilocal marriage rate (U) are sensitive to small changes in W. In considering the effects of W and s, we must bear in mind that, to simplify the model, we assumed that economic development led to a general level of wealth sufficient for everyone to afford a brideprice (i.e. $W = 1$), and thus that cultural beliefs could potentially prevail in determining marriage form. However, as the stochastic effects mitigating the cultural effects of σ_1 weaken—for example, as public health measures reduce mortality—and thus the cultural effects of σ_1 become stronger (i.e. as s goes to 1), the frequency (x) of σ_0 also increases. Thus, ironically, these assumptions mean that the increasing importance of the idea σ_1 for the frequency (U) of the practice (an effect that might be thought of as the increasing 'strength' of the belief in the population) allows a concurrent spread of the neutral belief σ_0. This result of combining the general model with the Danei data runs directly counter to the prediction of the general model (discussed above) that as s goes to 1, σ_1 should be dominant over σ_0. This unexpected result could be interpreted to mean that there is more cultural variability in the wealthier population. On the surface, this interpretation seems compatible with current marriage practice in Taiwan, where ethnographic evidence suggests that rural marriages are overwhelmingly virilocal and urban marriages are increasingly neolocal (i.e. where bride and groom establish an independent household), perhaps the ultimate expression of neutrality (cf. [63–67]). The result could also mean either that cultural ideas are less important in general than anticipated (and allowed for in the general model), or that cultural niche construction—changes in whether particular ideas are accepted as meaningful (i.e. shared, abstract, public and truth to some percentage of the population)—is more important and thus leads to a qualitatively different outcome from expectations.

The model also yields a lower bound for s (0.673) that is higher than we would expect based on empirical data of sibling composition as an effective predictor of uxorilocal marriage. As discussed above, when s is high, the cultural idea strongly influences practice, and $s = 0.673$ is a fairly high value for s. Recall that sibling composition is one of the best predictors of uxorilocal marriage [30,39–41]. This empirically documented sensitivity suggests that we ought to find a low value for the lower bound of s, yet we do not. Several assumptions in the model could affect the empirical validity of this lower bound: random mating with regard to σ, unbiased vertical transmission, gender neutrality with regard to σ and s, and s constant. Changing any of these assumptions would make the model substantially more cumbersome, but these may be valuable changes to consider in the future.

6. CONCLUSIONS

This model and its connections to the empirical case of changing marriage form in Taiwan yield several general conclusions about the construction of human cultural niches and the value of distinguishing between social and cultural niches. They indicate the kind of empirical data that would facilitate future models, and they suggest a potential for building bridges to the social sciences.

(a) *Culture is in constant flux*

Table 3 and figure 5 together demonstrate that, in all projections, the frequency (x) of the cultural idea σ_0 changes. Even in projection 3, x changes slightly ($x_4 = x_3 = 0.196 > x_2 = x_1 = 0.195$). In other words, human cultural niches—like ecological niches—are in constant flux. This conclusion fits with our conception of a cultural niche as the sum of all cultural selection pressures, which in turn derive from transmission processes (including broadcasting, reception and internalization of ideas) and interactions between cultural ideas. Shifts in belief by individuals constitute bits of change—constant flux—constructing the cultural niche. Such incremental change would only be noticeable at a population level when a significant number of people changed in the same way. Thus flux goes on constantly at the individual level but is only visible at the population level under certain kinds of conditions, which suggests both that we should expect drift (i.e. stochastic effects in small populations) to influence cultural change [16] and that cultural persistence (e.g. [7,68]) requires explanation.

(b) *Phenotype is not a reliable indicator of culture*

Figures 4 and 5 show that the frequency of a cultural unit—an idea or belief—need not correspond to the frequency of the associated practice (phenotype). Consequently, we cannot determine the content of the ideational pool—the cultural niche—on the basis of the frequency of customs.

(c) *Culture is sensitive to society*

Table 3 indicates that even small society-wide changes in economic development may result in larger shifts in cultural content, measured in the increasing frequency (x) of the belief σ_0, and the stronger influence (s) of the belief σ_1, providing further evidence of the importance of including social factors in cultural evolution models.

The results of linking the general model to the Danei data raise several possibilities for future exploration. Wealth may increase the cultural variability in the population. Cultural ideas may be less important motivators of behaviour than social factors. Cultural niche construction may result in change that qualitatively departs from expectations based on cultural selection pressures alone. All of these possibilities would be best explored using models integrated with empirical data.

(d) *Including culture and society yields more realistic models*

The introduction of even highly simplified social effects leads to a more realistic model of cultural change. The modelled sensitivity of the uxorilocal marriage form to population-level economic development agrees with Wolf's [39] conclusions about the sensitivity of minor marriage to economic development in northern Taiwan. Moreover, when s is understood as mitigating social effects, its inclusion can realistically result in a Han population with a high frequency of disapprobation of uxorilocal marriage (the idea σ_1) that nevertheless maintains a noticeable frequency of uxorilocal marriage (phenotype) owing to stochastic effects on sibling composition.

(e) *Modifying the model requires quantitative empirical data*

This model is linked to one specific case study, which has allowed us to obtain specific estimates of the model parameters and projections of changes in the economy (W) and the frequency (x) of the culturally neutral idea (σ_0) that may underlie the changes in the uxorilocal marriage rate (U). However, the model can be generalized to examine the contributions of cultural and economic factors in other case studies of changes in human customs, or further specialized to be more realistic for a particular case study, if adequate quantitative data are available.

For example, fitting this model to a case study of rapid change in a different time or place requires reliable data on the changing frequency of the practice over time as well as a general estimate of the economic population index for at least one cohort in the time period under consideration. To make our model more realistic, for example, to consider whether the coefficient of horizontal transmission (H) depends on the prevalence of uxorilocal marriage (U) or more directly on the prevalence (x) of cultural belief σ_0, would require reliable quantitative data not only on the frequency of practices across individuals but also on the frequency of associated ideas. It would also be beneficial to have an empirical understanding—and even better, an estimate—of H, the influence of peers on ideas or beliefs. Thus, the model suggests the importance of developing reliable methods for quantifying ideas independently of quantifying behaviours (see [10,50,61] for brief discussion of such methods).

(f) *Realistic models promote social science collaborations*

We suggest that the potential for increased specificity and realism generated by niche-construction models that incorporate social as well as cultural effects on human culture can facilitate building bridges to the social sciences. We think that the implications of the findings presented here move evolutionary models of cultural change towards empirically based research in anthropology and sociology. Niche-construction models have the potential to capture many realistic elements: separation of custom (phenotype) from belief, influence of economics, social stratification, family composition and—perhaps most importantly—the recognition that culture and society are cumulative and inherited, not reinvented in each generation.

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APPENDIX

In order to calculate the lower and upper bounds for s, shown in equation (5.1) in the text, we begin by re-writing equation (3.1) as

$$W = \frac{2(1-U)}{1+s(1-x)(2-s[1-x])}. \qquad \text{(A 1)}$$

We also solve equation (3.1) for x, keeping in mind that, by definition, $0 \le x \le 1$:

$$x = 1 - \frac{1-\sqrt{2(1-(1-U)/W)}}{s}. \qquad \text{(A 2)}$$

Solving for s, we can rewrite equation (A 2) as

$$s = \frac{1-\sqrt{2(1-(1-U)/W)}}{1-x}. \qquad \text{(A 3)}$$

To obtain the lower bound for s, we note that, because $W_4 = 1$ and U_4 is lowest value of U, the numerator of the right-hand side of equation (A 3) will be lowest for cohort 4 (1936–1945) as well. Moreover, horizontal transmission cannot reduce a non-zero value of x to zero. In other words, if we assume that x is non-zero in any of cohorts 1 to 3, then x_4 can approach, but may not equal 0 (i.e. $x_4 > 0$). Finally, we substitute $U = U_4$, $W = W_4 = 1$ and $x = x_4 = 0$ into equation (A 3) to calculate the lower bound on s:

$$s_{\text{low}} = 1 - \sqrt{2U_4}. \qquad \text{(A 4)}$$

From (A 4), since $U_4 = 36/671$ (data in figure 2), $s_{\text{low}} = 0.6724293$.

Because x_4 is strictly greater than 0, we know that s is strictly greater than s_{low}. Moreover, since x_4 may approach 1, and $s \le 1$ by definition, a similar analysis of equation (A 3) shows that s is bounded above by 1. In sum, s could be anywhere within the interval (s_{low}, 1).

In order to calculate x_4, shown in equation (5.2) in the text, we substitute $U = U_4$, $W = W_4 = 1$ into equation (A 2) and obtain x for time period 4 (1936–1945) in terms of s and U_4:

$$x_4 = 1 - \frac{1-\sqrt{2U_4}}{s} = 1 - \frac{s_{\text{low}}}{s}. \qquad \text{(A 5)}$$

To solve for x_4, we must choose a value within the half-closed interval for s. We start with s just above the lower bound of its range, $s = 0.673$. Given this value, $x_4 = 0.000847994$.

In order to calculate W_1, we remember that W is constant for the entire population but variable between time periods. We focus on one subsection of the population for which we have U and an estimate of x in time period 1 (1906–1915): the Danei Han who lived and married outside Toushe. Thus, we set $U = U_{\text{H1}}$ and $x = x_{\text{H1}} = 0$ in equation (A 1) to obtain W_1 in terms of s and U_{H1}:

$$W_1 = \frac{2(1-U_{\text{H1}})}{1+s(2-s)}. \qquad \text{(A 6)}$$

For a given value of U_{H1}, W_1 is strictly less than the value obtained when $s = s_{\text{low}}$. If we substitute the empirical value of $U_{\text{H1}} = 69/326$ (data in figure 2) and $s = 0.673$ into equation (A 6) we obtain $W_1 = 0.8328727$.

In order to calculate x_1, we modify equation (A 2) to calculate the overall prevalence of σ_0 in time period 1:

$$x_1 = 1 - \frac{1-\sqrt{2(1-(1-U_1)/W_1)}}{s}. \qquad \text{(A 7)}$$

Entering the empirical values of U_1 (103/423, data in figure 2), $s = 0.673$, and $W_1 = 0.8328727$ into equation (A 7), we obtain $x_1 = 0.150437$.

In order to calculate H, we begin by writing down equation (3.2) for the transitions between cohorts 1 and 2, cohorts 2 and 3 and cohorts 3 and 4:

$$x_2 = x_1 + H x_1(1 - x_1), \quad (A\,8a)$$

$$x_3 = x_2 + H x_2(1 - x_2) \quad (A\,8b)$$

$$\text{and } x_4 = x_3 + H x_3(1 - x_3). \quad (A\,8c)$$

We substitute all instances of x_2 in the right-hand side of equation (A 8*b*) with the right-hand side of equation (A 8*a*). The result is a cubic polynomial in H:

$$x_3 = x_1[1 - 2H(1 - x_1) + H^2(1 - x_1)(1 - 2x_1) + H^3 x_1(1 - x_1)^2]. \quad (A\,9)$$

A similar substitution of equation (A 9) into the right-hand side of equation (A 8*c*) yields a 7th-degree polynomial in H:

$$\begin{aligned} x_4 = x_1[&1 - 3H(1 - x_1) + 3H^2(1 - x_1)(1 - 2x_1) \\ &- H^3(1 - x_1)(1 - 9x_1 - 9x_1^2) + 5H^4 x_1(1 - x_1)^2 \\ &+ H^5 x_1(1 - x_1)^2(1 - 8x_1 + 8x_1^2) \\ &+ 2H^6 x_1^2(1 - 2x_1)(1 - x_1)^3 + H^7 x_1^3(1 - x_1)^4]. \end{aligned} \quad (A\,10)$$

In general, equation (A 10) will yield seven possible values of H for any particular values of x_1 and x_4. However, up to six of these values may be complex. Any of the values that are real, greater than -1 and less than $+1$, constitute a possible value for H that satisfies all the requirements for this parameter within our model.

For instance, we can substitute the values of x_1 and x_4 that correspond to $s = 0.673$ (i.e. $x_1 = 0.150437$ and $x_4 = 0.000847994$) into equation (A 10), obtaining:

$$\begin{aligned} 0.000847994 = 0.150437 \times (&1 + 2.54869H \\ &+ 1.78185H^2 - 0.127648H^3 \\ &- 0.379552H^4 + 0.00243713H^5 \\ &+ 0.0194036H^6 - 0.00177356H^7). \end{aligned} \quad (A\,11)$$

Using MATHEMATICA, we solve this equation and obtain the following seven possible values for H, -3.06104, $-1.16266 - 0.137671\,i$, $-1.16266 + 0.137671\,i$, -0.871687, 3.11696, 6.41389 and 7.66765. (Here, i equals the square root of -1.) Since only one of these is a real number between -1 and 1 ($H = -0.871687$), that is the value we use to calculate x_2 and x_3.

Given $H = -0.871687$ and $x_1 = 0.150437$, we can solve equation (A 8*a*) to obtain $x_2 = 0.03903042$. Substituting this value of x_2 and the same value of H ($-0.871\,687$) into equation (A 8*b*) yields $x_3 = 0.006\,336\,015$.

Once we have x_2, we can substitute U_2 and x_2 into equation (A 1) to yield W_2 in terms of these variables and s:

$$W_2 = \frac{2(1 - U_2)}{1 + s(1 - x_2)(2 - s[1 - x_2])}. \quad (A\,12)$$

Once again, we can substitute the empirical value $U_2 = 92/488$ (data in figure 2) along with $s = 0.673$ and $x_2 = 0.03903042$ into equation (A 12) to obtain $W_2 = 0.8654805$.

The method for calculating W_3 is similar:

$$W_3 = \frac{2(1 - U_3)}{1 + s(1 - x_3)(2 - s[1 - x_3])}. \quad (A\,13)$$

Substituting $U_3 = 93/744$ (data in figure 2), $x_3 = 0.006336015$ and $s = 0.673$ into equation (A 13) yields $W_3 = 0.9257966$.

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