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Effects of Changes in Traditional Agroecosystems on Vernacular Dwellings: the Occupants' Perspective

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Abstract
Dwellings have an important role in human adaptation to their environment; it is therefore crucial to understand how people deal with variations in building materials. We studied the impact of transforming traditional agroecosystems on the perishable materials used to build vernacular dwellings in a Maya community in central Yucatan, Mexico. Occupants and builders identified traditional agroecosystems as the main source of traditional materials. Our informants cited fragmentation of landholdings and land use intensification of traditional agroecosystems as the main reasons for the decreasing availability of traditional materials, which, together with their perishable nature have led to their replacement by industrially produced materials, predominantly by households with limited involvement in agricultural activities.

Keywords Agroecosystems · Home gardens · Milpa · Maya houses · Vernacular buildings · Fragmentation of landholdings · Land use intensification · Yucatan · Mexico

Introduction

Human adaptation to their local environment is driven not only by the selection of genetically-based phenotypic traits but also by the ability to transform their habitat and their culture (Creanza and Feldman 2006; Futuyma and Kirkpatrick 2017). Additionally, their dwellings may have a crucial role because they are the primary anchor of an individual in his or her environment and offer primary functions such as concealment and shelter (Coolen 2006). From an ecological perspective, a dwelling represents a subsystem of settings where only a subset of human activities takes place embedded in a larger system called the environment (Coolen 2006; Lawrence 2006). Dwellings also represent a microcosm of larger social and cultural values, and an arena where these values interact with the environment to create a natural balance (Bourdieu 1970). Therefore, in societies with a high degree of dependence on primary activities, one would expect there to be a strong interplay between dwellings and their surroundings, especially those that are intensively managed, such as traditional agroecosystems.

Vernacular dwellings are a beautiful example of a built environment that is highly adapted to the local environment and heavily influenced by culture (Rapoport 1969, 1982). Although the definitions vary, there is some agreement among authors that vernacular dwellings are essentially built by non-experts (frequently the prospective occupants are involved) using local materials (Rapoport 1969; Bowyer 1980; Brunskill 1986). Because vernacular dwellings typically use local and perishable materials (Rapoport 1969) they are a reliable indicator of changes in the availability of raw materials and patterns of resource use in local ecosystems. It is known that local ecosystems are affected by several environmental (e.g., climate change, pests, soil erosion; Altieri and Koohafka 2008), socioeconomic (e.g., urbanization, migration; García-Barrios *et al*. 2009), and cultural (e.g., changes in gender roles, social status and stereotypes, Ascencio *et al*. 2014) variables. For example, in some rural regions of Mesoamerica, traditional building materials are scarce and with current globalization non-local building materials are now available in formerly isolated communities; concomitantly, migration to the United States of America has contributed to the adoption of new stereotypes in terms of dwellings (Ascencio *et al*. 2014). In this context, new materials and new construction techniques are eventually incorporated into

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the construction of vernacular dwellings and, as a result, changes in these dwellings are increasingly evident.

People living in traditional non-western societies in rural settlements spend relatively little time in their dwellings (mostly late afternoons and nights), with adults spending most of their time in traditional agroecosystems (e.g., Baños 2002; Boils 2013) that provide not only fruits and vegetables, but also their building materials (Rico-Gray *et al*. 1991; Caballero 1994; Ochoa-Winemiller 2004; Pulido and Caballero 2006). Additionally, these agroecosystems are also the setting for the oral transmission of construction knowledge over the generations (Ochoa-Winemiller 2004; Sánchez-Suárez *et al*. 2017). Therefore, it is not difficult to predict that any phenomena that affect traditional agroecosystems could impact vernacular dwellings either directly (i.e., availability of plant materials) or indirectly (via transmission of construction knowledge). Current research on contemporary vernacular dwellings in traditional, non-western societies (mainly Asia and Mesoamerica) has focused on the gross changes in building materials (local vs. industrial materials) triggered by socioeconomic processes such as migration and urbanization (e.g., Toffin 1994; Pinijvarasin 2003; Ettinger 2010; Punpauiroj 2013; Ascencio *et al*. 2014; Sánchez-Suárez *et al*. 2017). However, the way in which vernacular builders deal with changes in the availability of materials resulting from the transformation of traditional agroecosystems is poorly understood.

We looked at changes in building materials and the spatial configuration of vernacular dwellings in a lowland Maya community located in central Yucatan. We also assessed whether these changes were linked to changes in traditional agroecosystems (i.e., landholding fragmentation, use intensification, crop change, etc.) in the lifetime of their occupants primarily from their perspective. We specifically focused on perishable materials obtained from plants (wood, lianas, leaves, and trunks) because, owing to their short lifespan, these are good indicators of recent and rapid changes in the composition of these agroecosystems. The Maya are strongly linked to traditional agroecosystems not only in terms of food (Villers *et al*. 1981; Rico-Gray *et al*. 1991), but also culturally (Terán and Rasmussen 2009). Traditional agroecosystems such as the milpa (itinerant polyculture with maize, beans, and squash as the main crops) and their dwellings are also closely related to Maya cosmogony (Gillespie 2000; Barrera-Bassols and Toledo 2005), which describes the creation of the universe in terms of house building and milpa cultivation (Gillespie 2000; Sánchez-Suárez *et al*. 2017). In traditional swidden cultivation, not only the milpa but also all stages of forest succession are being managed (Nigh and Diemont 2013). Therefore, in a sense, the forest can be seen as an extension of traditional agroecosystems (Gómez-Pompa 1987; Ford and Nigh 2003; Nigh and Diemont 2013). The milpa is a living tradition, especially in central Yucatan, a region known as a *zona maicera* (region of maize production in Spanish; Sohn *et al*. 1999) where our study area is located. Unfortunately, the traditional milpa has undergone a drastic transformation in recent years due to land fragmentation, a reduction in the number of crops, and land use intensification (Terán and Rasmussen 1995; Sohn *et al*. 1999).

The traditional Maya house has long intrigued scholars. This is perhaps because contemporary houses look similar to those of the ancient Maya of ca. 3,000 years ago (Gerhardt and Hammond 1991; Hammond 2001, 2008). It is unlikely that material availability has not changed over such a long period of time. Currently, some authors think that the collapse of the Maya during the Classic period (300–900 AD) was related to a dramatic reduction in productivity and the overexploitation of both traditional agroecosystems and forests (Turner 1974; Abrams and Rue 1988). A likely explanation for the high degree of resilience of the Maya house is the ability of builders to obtain similar results using different materials. Most studies of changes in the Maya house have focused on the dichotomy of traditional vs. industrial materials (e.g., Pérez 1993; Tello-Peón 1993; Chico Ponce de León 1995) and have neglected changes in plant species, despite the fact that this implies extensive experimentation with novel resources (Alecar *et al*. 2010). We predicted that recent dramatic changes in traditional agroecosystems have promoted concomitant changes in plant materials used to build vernacular dwellings. Our specific research questions addressed the main changes perceived by the occupants of vernacular buildings regarding perishable materials, and whether these changes related to changes in traditional agroecosystems.

Materials and Methods

Study Area

The study was conducted in the municipality of Sotuta, located in the central part of the Yucatan Peninsula (20° 35′ 45” N, 89° 00′ 22” W, 21 m.a.s.l.). This locality lies within the *zona maicera*, an area with an ancient tradition of maize cultivation (Sohn *et al*. 1999). The weather is warm, sub-humid with summer rains (annual precipitation: 1,257 mm; INEGI 2009; SMN 2016). The dominant soil (90%) in the region, known as leptosol, is shallow and rocky (INEGI 2009). Surface water is very scarce and ephemeral, thus water for drinking and agriculture is obtained from the subsoil and rain (Sohn *et al*. 1999). The study area was the main town where most of the vernacular buildings are located together with home gardens as well as milpa, which is usually located a few hundred meters to a few kilometers away from the dwelling. Thus, the study area covers about 660 ha. In 2010, there were 8,449 people living in 2,059 dwellings in Sotuta, an average of 3.8 people per dwelling (INEGI 2010). The mean number of years

of formal education is 5.5 years; typically the head of the household is a man, with only 16% of the dwellings having a female head (INEGI 2010). The main economic activities are agriculture and more recently, salaried work, mainly as bricklayers (men) and domestic help (women) in the tourist cities of the Peninsula (Riviera Maya, Cancún, and Mérida; Fraga 2012). Most people have Mayan ancestry and 52% speak Maya as their mother tongue (Fraga 2012).

Sampling

The unit of analysis was the domestic group (defined as the set of people sharing the same living space; Segalen 1986) and their dwelling. We selected 64 domestic groups that owned a vernacular house representing a gradient of substitution of local materials as follows. Typical vernacular dwellings (41%) have an apsidal base, walls made of bahareque (interwoven reeds or sticks held together with a mixture of wet earth and straw) and a roof made of xa'an palm (*Sabal yapa*) and/or grass (*Melinis repens* and/or *Gouinia latifolia*). Hybrid dwellings (49%) have an apsidal base, partial and complete masonry walls, and roof made of xa'an palm. Severely transformed dwellings (10%) have an apsidal/rectangular base, masonry walls, and flat, concrete roofs. The dwellings selected represented 22% of the population. Sampling was non-probabilistic because we depended on the agreement of house occupants to participate in the study. We initially contacted a woman (76 years old) who is well known and respected in the community. She helped us to locate and make contact with some of the domestic groups living in vernacular dwellings. Following their agreement to participate in the study, we located further domestic groups using the snowball sampling approach. We excluded contiguous dwellings and tried to avoid spatial clustering (study units were approximately homogenously distributed throughout the study area) in order to maintain independence among the units of analyses. With the help of these informants, other key informants, not members of the sampled domestic groups, were identified: vernacular builders ($n = 6$), and producers/sellers of xa'an palm ($n = 4$). The total number of informants was 111 (57 men and 54 women), and all of the men had been born in Sotuta, as had the majority of the women (88%), with the remainder born in the same region, near Sotuta. Informants had a mean age of 58.58 ± 13.78 (men) and 56.56 ± 13.78 (women). Most of the male informants reported agriculture (68%) and construction (32%) as their main economic activities. The vast majority of female informants self-reported as housewives (84%).

Characterization of Dwellings

During the summer and winter of 2016, we described the dwelling for each study unit in general terms. In the study units with more than one building, we chose the oldest building, typically located at the main entrance from the street (Sánchez-Suárez 2006). Descriptions were based on direct observation, photographs, and some specific information obtained from occupants by asking direct questions. The descriptions included the materials and finishes, as well as the state of the floors, walls, and roofs.

Interviews and Participant Observation

We used semi-structured interviews to ask the occupants about the main modifications made to the dwelling during the time they had lived there and the motivation behind them. Additionally, we asked about the age of the dwelling, the original builders, and who has been repairing the house. Finally, we asked the occupants about their current and past economic activities and for some biographic information.

Unstructured interviews were also conducted with other key informants (farmers, vernacular builders) regarding the main transformations to agricultural activities in Sotuta and whether or not they perceived any link between agricultural activities and the availability of the raw materials used to build vernacular dwellings. Additionally, we interviewed (unstructured interviews) the sellers of both traditional ($n = 2$) and industrialized ($n = 2$) materials regarding the availability of local and perishable materials traditionally used and the factors that had influenced their replacement by industrialized materials in vernacular dwellings.

Participant and non-participant observation was conducted during the interviews, including four visits to milpas and surrounding forests to see where and how local materials were obtained.

The interviews were conducted in Spanish; no Maya interpreter was needed because all the interviewees spoke some Spanish as their first or second language. All of the relevant information that was not recorded during the formal interviews was noted in a field diary. When verbal consent was given, interviews were audio-recorded. All informants gave their verbal consent for us to use the information they provided for academic purposes.

Data Analyses

With the data on the characterization of dwellings that we obtained, an index of substitution of the local, perishable material was calculated. The components of this index were the main elements of the building (floor, socle, walls, internal and external finishes, ties, as well as the roof). For each element, a scale of 3–5 points was assigned per element. When local, perishable materials were used, a value of zero was assigned and when industrialized materials were used, a value of 10 was assigned. When a combination of materials was used, intermediate values were assigned, depending on the relative predominance of industrial materials (i.e., when industrialized

materials were dominant, assigned values approached 9). The sum of the values given to each of the elements was the index of substitution of local, perishable materials. Index values close to zero indicate that the materials used in that specific dwelling were mainly local and perishable, while values close to 70 (maximum value) indicate that a dwelling was almost entirely built with industrialized materials (see Supplementary Material).

To calculate an index of agricultural dependence to measure the degree of involvement of each domestic group in activities associated with traditional agroecosystems, we identified the main agronomic activities of the domestic group: milpa, apiculture, cultivation of xa'an palm in the home garden, cultivation of other crops in the home garden, breeding farm animals in the home garden, raising livestock (fewer than 8 animals), and assigned a value to each: 0 = no activity; 5 = intermittent involvement; 10 = frequent or permanent involvement. The final value of the index was the sum of all values for each activity. The minimum value of the index was zero and represented a domestic group with no involvement in activities related to traditional agroecosystems, and values approaching the maximum (60) indicate increasing involvement in activities associated with traditional agroecosystems.

To assess whether there was an association between the agricultural dependence index and the index of substitution of traditional materials we conducted a Pearson's correlation analysis.

We transcribed the data obtained from the interviews, codified it, and organized it into thematic categories. Then, we identified recurrent descriptions of situations and associations. We were particularly interested in identifying elements in the discourse of informants that suggested an association (or the lack thereof) between modification of the dwelling and activities in traditional agroecosystems. The information obtained during participant and non-participant observation was used as context for the interpretation of the data.

Results

Characterization of Dwellings

According to the occupants, the mean age of the dwellings sampled was 54.66 ± 30.63 years, an apsidal shape of the base was far more frequent (90.63%) than rectangular (6.25%) or irregular (3.12%). Most of the dwellings have a masonry socle (70%), in some dwellings it is made of rock with no mortar (19%) and the rest (11%) it is made of reinforced concrete. The majority of the dwellings had a floor made of mortar (84.38%), some are also covered with tiles (14.06%), and the rest (1.56%) are rammed earth. The majority of the walls are made of bahareque (43.75%), followed by masonry (31.25%), and concrete blocks (12.5%). Hybrid techniques such as masonry + bahareque (9.38%) as well as masonry + concrete block (3.12%) also occur. Dwellings with bahareque walls have tree trunks supporting the roof (Okom in Maya, plural: Okomo'ob). However, in dwellings with walls of non-perishable materials, the Okomo'ob are sometimes absent (18.75%) and the roof is supported by the walls or concrete columns. Wall cladding is mainly of mortar (42.19%) or pa'lu'um (adhered soil; 35.94%), which is a plaster made of earth and grass. Hybrid techniques are also seen in wall cladding (21.87%) associated with repairs made or requested by the occupants. The majority (75%) of roofs were made of xa'an palm and only 7.81% were made with red grass (*M. repens*) or chak su'uk (terms used to refer to either *M. repens* or *G. latifolia* indistinguishably; 3.78%). Hybrid techniques (4.69%) were also associated with repairs. The roofs of the remaining dwellings had been completely replaced by commercial materials such as cardboard (4.13%) or concrete (4.68%). The roof ridge (pa' jo'ol in Maya) is made of galvanized metal sheets in all dwellings except one, where it is made of xa'an palm. In 55% of dwellings, trunks were tied together with lianas (*Cydista potosina*). In the others (13.33%) nails, screws, or wire was used. As for other elements, hybrid techniques (31.67%) were associated with repairs.

Patterns in the Substitution of Building Materials

Based on the architectural characterization of dwellings and the information provided by the occupants during the interviews, we identified a pattern of material substitution that ranged from dwellings made of mainly local, perishable materials to primarily industrialized materials, though the shape and functionality of the dwelling remained essentially the same (Fig. 1). All evidence suggests that the archetype of vernacular dwelling in Sotuta has a socle made of rock with no mortar, walls of bahareque with pa' lu'um cladding, and roofs (including the ridge) made of grass (Fig. 2). One remarkable transition was the substitution of grass in roofs for xa'an palm and the use of a galvanized sheet as the ridge, as well as the use of a masonry socle instead of rock (Fig. 1a). The occupants mentioned that sometimes this modification occurred simultaneously with the partial substitution of bahareque walls for masonry; dwellings built this way are locally known as half ripio (Fig. 1b). In a second stage of modification, bahareque walls were completely replaced with masonry walls (also known as ripio; Fig. 1c), concrete block (Fig. 1d), or a mix of masonry and concrete block (Fig. 1e). Finally, the extreme of the modification gradient was represented by dwellings with roofs made of cardboard sheets (Fig. 1e) or even more extreme, flat roofs made of concrete (Fig. 1f); 34% of the latter were built with the aid of a government subsidy (Fund for natural disasters: FONDEN) made available when Hurricane Isodoro hit the Yucatan Peninsula in 2002; this program continues to the present.

Motives behind Material Maintenance or Replacement

Although most of the occupants interviewed said that they are happy living in a vernacular dwelling and did not identify any drawbacks (65.6%), others (17%) mentioned the limited durability of perishable materials as a major drawback. Less frequently mentioned drawbacks to these materials were: the presence of potentially harmful animals (mosquitoes, scorpions, poisonous snakes; 8%) and vulnerability to environmental hazards such as hurricanes and fire (9.4%). To the occupants, these drawbacks completely justified material substitution. A widely conserved element in vernacular buildings was the roof made of xa'an palm or grass, and the thermal property of these roofs was the most valuable property of vernacular dwellings according to 40% of occupants. One woman notes: "Many people say that they like this little house because it is cool" (housewife, 66 years old). Some occupants had modern constructions with concrete roofs in addition to a vernacular dwelling on their land, and frequently mentioned that the vernacular dwelling is comparatively cooler than modern dwellings with concrete roofs, though they also appreciated the greater durability of the latter: "I changed (the roof) because when you replace palm with concrete, you do not have any more problems (referring to repairs)... however, during the dry season, it is very hot" (Peasant, 55 years old).

Fig. 1 Examples of vernacular dwellings seen in Sotuta, Yucatan, Mexico showing a gradient of material substitution (from mainly local, perishable to mainly industrially produced materials). **a** Traditional dwelling with masonry socle, bahareque walls and pa'lu'um cladding; the roof is partially made of grass and xa'an palm with a galvanized sheet as the ridge. **b** Half ripio. Bahareque has been partially replaced by masonry walls with cladding made of mortar. **c** Ripio. Walls are completely made of masonry and mortar claddings in parts. **d** Ripio with walls made of concrete block. **e** Dwelling with roof made of sheets of cardboard. **f** Dwelling with a plain roof made of concrete

Traditional construction knowledge is currently limited, and informants indicated that in the past the majority of the vernacular buildings were self-constructed with the help of family and friends. However, nowadays only a few people have the skills to build vernacular dwellings so the most people pay someone else to do it. Fifty percent of vernacular builders learned the construction techniques from their parents; however, all informants agreed that there is currently much less interest in learning these techniques. The remaining 50% of builders learned these techniques from a non-relative while working as a helper: "…I was taught by my deceased father …" (Builder, 65 years old); "… I was taught by the neighbor … his son did not help him …" (Builder and peasant, 69 years old). Vernacular builders reported an income ranging from 150 to 200 Mexican pesos (approximately 7–10 US dollars) per day. All the builders interviewed have worked outside Sotuta, mainly in the tourist region of the Caribbean, about 240 km away. Builders who specialize in the construction of palm roofs are locally known as *palaperos* (palapa builder), and also build palm roofs for cottages, restaurants and hotels. Most male family heads (72.5%) reported some involvement in minor repairs; however, the rest (22.5%) reported that their day job makes repairs difficult or even impossible and thus they have to pay vernacular builders for repairs: "… When I am out (at work), I pay for repairs; I can only help on Sundays …" (Bricklayer, 35 years old).

Vernacular builders also possess relevant knowledge about the plant species used in vernacular dwellings. For example, they use species-specific plant names in Maya, e.g., xa'an

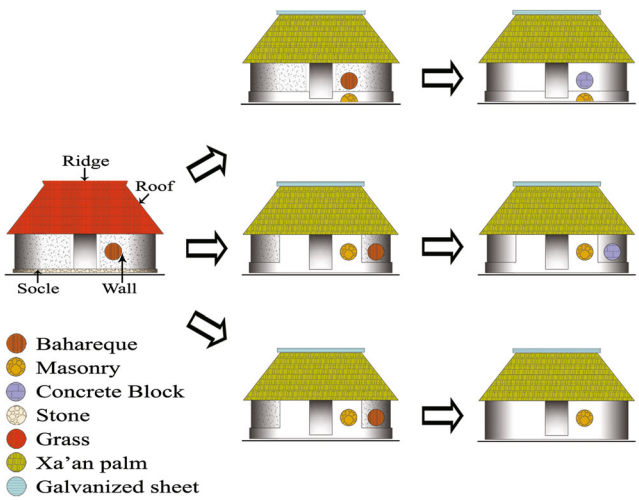

Fig. 2 Schematized temporal trajectories of material replacement observed in the main elements of vernacular dwellings (socle, walls, roof and roof ridge) in Sotuta, Yucatan. The dwelling on the left represents the most probable archetype. Three main trajectories departing from the archetype in terms of material replacement were identified during field work

(*Sabal yapa*), bojon xa'an (*Sabal Mexicana*), kitin che' (*Caesalpinia gaumeri*), chak te' (*Caesalpinia mollis*), Y'aax eek' (*Pithecellobium tortum*). They also use the corresponding functional nomenclature for architectural features, e.g., okom (main column), wíinkil che' (thin wood), beel ch'o' (mouse path), pa' jo' ol (roof ridge). Given the low availability of traditional materials, the cost of erecting vernacular and modern dwellings is comparable. A peasant aged 54 said, "It costs the same as building a modern house (referring to vernacular dwellings), we have to buy everything."

During the interviews some occupants (53%) mentioned an emotional attachment (usually stemming from childhood memories) to vernacular dwellings as an important factor in maintaining this type of building despite the elevated cost: "...I was brought up there from the time I was a little girl (referring to a vernacular dwelling), I would never get used to a different type of house ..." (Housewife, 61 years old); "I grew up in a house made of palm and I said one day my house will be like this ... I had the chance to build my house with concrete but, I like the houses made of palm" (Bricklayer, 35 years old); "My children were born here (referring to her vernacular dwelling)" (Housewife and artisan, 53 years old). Aesthetic considerations were also mentioned by 10.94% of the occupants: "… what I like the most, is the shape of it…" (Housewife, 72 years old); "... I think it is beautiful (referring to his vernacular dwelling)..." (Farmer and bricklayer, 45 years old). Some informants mentioned that vernacular dwellings are elegant or luxurious because similar structures can be seen in hotels, restaurants, or just because these are rented by foreigners in the tourist area on the Caribbean in the Mexican state of Quinta Roo: "…It's a luxury (referring to the vernacular dwellings), if you go to Quintana Roo, these little houses are occupied by the gringos (Caucasian people)…" (Housewife, 53 years old).

Traditional Agroecosystems and Building Materials

Overall, our informants perceived a dramatic decrease in milpa cultivation in recent years. Currently, of 407 ejidatarios (co-owners of communal land), only 30% cultivated milpa on ejido land, and only 42% of our informants cultivated milpa on a regular basis. Some informants remembered that the milpa was a highly profitable activity in the past (about 50 years ago). The milpa not only met the domestic group's needs but also usually produced a surplus that could be sold to buy other basic products or satisfy secondary needs: "...50 years ago I used to cultivate a lot of milpa when CONASUPO (government-operated, public welfare stores) started to buy corn; I used to sell them two or three tons" (Farmer, 80 years old). "...We were wealthy, there were nine brothers and sisters, my father provided for us with just the milpa..." (Merchant and farmer, 61 years old). Fragmentation of ejido landholdings and productivity loss were identified as the main reasons for abandoning the milpa: "... We cannot sow crops, the plot of land is too small..." (Peasant, 59 years old); "... The land is not suitable for crops; I planted some orange trees but they died..." (Carpenter, 55 years old).

In Sotuta, when the sons get married, the new family typically builds on land that was formerly part of the husband's parents' home garden, separating their plot with piled rocks (albarradas in Spanish), and over time this results in increasing fragmentation of landholdings. In recent years, one strategy to expand landholdings and increase productivity has been forest clearing and the use of agrochemicals. With forest clearance and land use intensification, the availability of materials used for vernacular building has also decreased dramatically. During participant observation, we noted that trees were scarce in the surroundings of the milpas and most of them had not reached an appropriate size for use in building construction. The chukum tree (*Havardia albicans*) dominated the area we visited and other sites. Informants reported that in recent years this tree has become the main species used to build vernacular dwellings even though it is not the preferred species because its quality is suboptimal: "These trees (referring *C. alba* and *C. mollis*) are no longer present in the ejido, only the chukum tree dominates nowadays..." (Peasant, 51 years old). Preferred timber species are only available in remote areas with limited access so extraction is not cost-effective: "...There is some mature forest from which timber could be extracted but, there is no road; that is why it has not been cleared yet ..." (Peasant, 61 years old).

As noted earlier, in the past grass was used for both the roofs and wall cladding of vernacular dwellings were grass. Informants reported that red grass used to be cultivated after forest burning during traditional swidden milpa cultivation and consequently both the reduction in the area used for milpa and an increase in the use of herbicides have led to its replacement by xa'an palm: "... In the last 25 years, almost no one has cultivated red grass for houses..." (Peasant, 65 years old); "The grass does not get along with the spray (herbicide), it ruins it" (Peasant, 72 years old).

The milpa also used to be an important source of forage for animals raised in home gardens, and its decrease has thus also influenced the production of animal protein in home gardens: "... When you cultivate milpa and there's a harvest, you can raise pigs and chickens, without the milpa, it is difficult to do so..." (Farmer, 72 years old).

Xa'an palm used to be harvested from the forest; nowadays, however, only 1.56% of informants reported harvesting the palm from the forest. According to informants, most of xa'an palm used for building vernacular dwellings is now obtained from home gardens (85.94%) and orchards (7.81%); those with concrete or cardboard roofs (6.25%) did not use any. We did not see any xa'an palm in the milpas, although informants noted that it does grows in a specific microhabitat in some other milpas, such as rocky cavities.

Of those informants who used the palm for construction, 44% said that they had cultivated the xa'an palm that was in their home gardens, but the others (66%) said that its seeds are naturally dispersed by bats and so they are recruited naturally in home gardens: "Huano palm grows on its own, the bats bring it" (Housewife, 56 years old). People weed and occasionally water the seedlings, and when the plants are big enough harvest some of the leaves. From the perspective of the informants, the biggest problem with obtaining xa'an palm is the fragmentation of home gardens so that they cannot support its cultivation: "I cannot cultivate palm, the land is too small" (Peasant, 59 years old). According to informants, approximately 2000 leaves are needed to build an average roof; however, only 200 to 400 leaves can be harvested per season from a home garden of average size. Some informants (37.5%) said that they had to buy xa'an palm from others in the community, paying from 2.50 to 4.00 Mexican pesos per leaf (about US$0.19–0.31).

We found a negative and significant correlation between the index of agricultural dependence and the index of substitution of traditional materials ($r = -0.29$, $p = 0.02$, $t_{62} = 2.35$). That is, when domestic groups are more involved in agricultural activities, their dwellings are built mainly with traditional materials (Fig. 3).

Discussion

Although the shape of the majority of the vernacular dwellings in Sotuta are similar to those built before the arrival of the Spaniards (Hammond 2001, 2008), they vary widely in terms of building materials, ranging from predominantly perishable, local materials to predominantly industrialized materials. The fact that different materials are used to build similarly shaped dwellings indicates that builders actively explore and adapt to new materials and techniques. According to the occupants, the main reason behind material substitution was the low availability of local materials and their perishable nature. An important source of perishable materials in the study area is traditional agroecosystems (i.e., milpa and home gardens) and their surroundings. In fact, we found a negative correlation between the number of agricultural activities performed in traditional agroecosystems and the replacement rate of perishable by industrialized materials (Fig. 3). That is, a domestic group with a strong involvement in agricultural activities is more likely to use traditional materials in their dwellings. Therefore, we suggest that the recent transformation of traditional agroecosystems due to fragmentation of landholdings and use intensification has mediated changes in the materials used to build vernacular dwellings, at least to some extent.

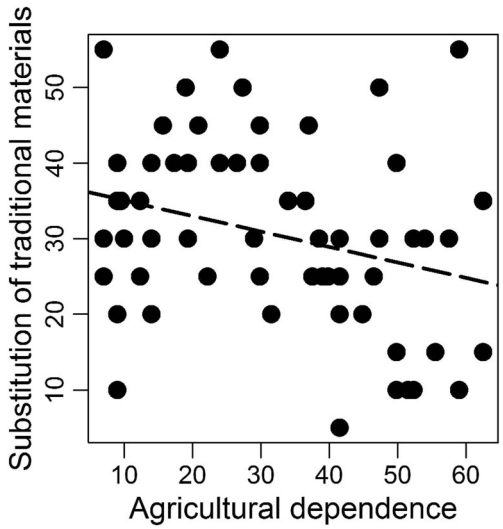

Fig. 3 Relationship between the index of agricultural dependence (Agricultural dependence) and the index of substitution of local, perishable materials (substitution of traditional materials) seen in 64 vernacular dwellings in Sotuta, Yucatan

According to the occupants, vernacular dwellings need to be repaired quite often owing to the limited durability of traditional materials. When occupants repair their dwellings, they usually find there is limited availability of the traditional materials that, only a few decades ago, were easily obtained from traditional agroecosystems and their surroundings. With the advent of globalization, commercial outlets of industrialized materials have opened in previously isolated, traditional communities, so that currently, where traditional materials are scarce and industrialized materials are accessible, the replacement of local, perishable materials by industrialized materials is both cost-effective and practical. A similar situation has been reported in other rural communities of Mesoamerica (e.g., Ascencio *et al.* 2011, 2014). It is likely that the continued use of local, perishable materials in vernacular dwellings will only be viable for domestic groups that have easy access to traditional agroecosystems.

Interestingly, even where industrialized materials are used, builders have tried to retain the shape of traditional vernacular dwellings. For example, in some dwellings built with rectangular concrete blocks the builders have managed to achieve the characteristic apsidal shape of vernacular dwellings (Fig. 1d). This suggests a strong attachment to vernacular dwellings and an adaptation to the new materials available. It has been suggested that this attachment stems not only from the occupants' subjective feelings about vernacular dwellings, but also from objective factors such as the inherent properties of the building, like indoor climate amelioration, an important consideration in Sotuta, where the daytime temperature can exceed 40 °C during spring and summer (INEGI 2009) (Singh *et al.* 2010; McGregor *et al.* 2016). The roof of vernacular dwellings plays an important role in passive thermal regulation because the plant material used absorbs and conducts little heat (Prieto 1978). This may explain why the palm roof is a highly

conserved element in vernacular dwellings in the study area and elsewhere on the Peninsula (Sánchez-Suárez *et al*. 2017).

Replacement of the traditional roofs by concrete seems to be the final step in the transition from the vernacular to a modern dwelling. The construction of flat concrete roofs always occurs when the floor and the walls have already been built with industrialized materials. Although the government has supported the building of dwellings with walls made of block and with flat concrete roofs to ameliorate the impact of natural disasters, these are unpopular in Sotuta because they do not take into account social preferences and local climate. Also, most of the informants did not perceive environmental hazards as a major threat when living in a vernacular dwelling. In contrast, another government program called *Pueblos Mágicos* (Magical Villages) promotes vernacular-shaped dwellings with walls made of block but with an apsidal shape and palm roofs as a part of a program to attract tourists to small villages in Mexico. To some extent, this program has contributed to maintaining local pride in and attachment to vernacular architecture (Onnis 2017). In Sotuta people migrate regularly (12% of men and 8% of women) to work in the tourist industry of the Caribbean (Cruz-Cortés 2017), an area where roofs made of xa'an palm are popular in tourist buildings. This has probably contributed to maintaining some people's attachment to vernacular dwellings compared to other villages in Mesoamerica where a large proportion of men migrate to the United States of America for long periods of time and send money back home to improve or build a new house based on a foreign stereotype (Ascencio *et al*. 2011, 2014).

The dichotomy of traditional vs. industrialized materials has received much attention by researchers interested in the evolution of the vernacular dwellings of the Maya of Yucatan Peninsula (e.g., Pérez 1993; Tello- Peón 1993; Chico Ponce de León 1995). However, in this study we also found an important turnover in the plant species used in vernacular dwellings that has received little attention. The ways in which communities incorporate new plant species into the pool of useful plants is a topic of recent and growing interest because it provides insight into how new ethnobotanical knowledge is produced (e.g., Alecar *et al*. 2010). As noted above, vernacular roofs used to be made of grass but in recent years only xa'an palm has been used. According to Spaniard chroniclers, palm and grass were both used to make roofs during the Spanish colonization of some parts of the Yucatan Peninsula (Landa 1938). Informants frequently used the terms "zacate" (grass), "zacate rojo" (red grass) and chak su'uk interchangeably. In the regional flora (http://www.cicy.mx/sitios/flora%20digital/vegetacion.html, last accessed 30th August, 2018), "zacate rojo" is the common name for *M. repens* (a species exotic to the study area; Melgoza-Castillo *et al*. 2014), and chak su'uk is used for *G. latifolia* (a native species; Ortíz 1993) and *M. repens*. Because both grass species look similar and because their relevant physical properties as a building material are almost identical, we do not think that our informants discriminate between them. It is very likely that vernacular builders inadvertently started using *M. repens* instead of *G. latifolia*, but this substitution did not represent a major transition. The decline of populations of these grasses noted by our informants likely results from the susceptibility of both grass species to the effects of herbicides. From 1990 to 2005 use of pesticides in the Yucatan increased 688% from 609 to 4800 t (Pérez *et al*. 2013). The use of herbicides in traditional agroecosystems and their undesirable effects on grass species also led to the abandonment of using pa' lu' um in walls and its replacement by mortar cladding.

The transition (or return) from grass to xa'an palm as a roofing material for vernacular dwellings was probably not difficult because neighboring communities in the region have been using this palm species for a long time. Interestingly, the ridge or pa' jo'ol is now rarely made of xa'an palm in Sotuta (but rather of galvanized sheets), though other localities in the region use this palm. Given the current scenario of scarcity of xa'an leaves in Sotuta, the use of galvanized sheets is the probably most cost-effective choice. Xa'an palm demographic studies done in another region of the Peninsula, X-Maben in Quintana Roo, suggest that the xa'an population is growing and leaf production is enough to meet demand in the near future (ca. 90 years; Pulido and Caballero 2006). However, available land (73,400 ha) and population size (2,980 habitants in the year 2000) suggest that the problem of declining traditional agroecosystem lands in this locality is far less severe than it is in Sotuta. Even though xa'an palm seedling recruitment occurs naturally in traditional agroecosystems, the xa'an population is very small because of the high degree of land fragmentation and the increasing intensity of use in Sotuta mainly due to the transition from extended to nuclear families in search of more privacy in the form of a separate house, usually built on the area formerly dedicated to the husband's parents' home garden (Cruz-Cortés 2017). In Sotuta, the population increased 75% (from 5190 to 8449) between 1980 and 2010; however, the number of people per house has decreased from 5.2 to 3.8. Concomitant socioeconomic processes such as expansion of the service sector of the economy and migration have also promoted land use change, mainly from agricultural to residential use.

Preferred timber species used in vernacular buildings are no longer available in some of the accessible locations in Sotuta. In their study, Villers *et al*. (1981) listed about 25 tree species used in the construction of vernacular buildings on the Yucatan Peninsula in the 1970s and mentioned that the Maya had a hierarchical list of timber plant species: when preferred species were not available, other species could be used but with suboptimal results (Villers *et al*. 1981). Nowadays, the number of species has dramatically decreased to the degree

that, in some parts of Sotuta the only available timber species is *H. albicans,* a species that, from the perspective of informants, performs poorly in the construction of vernacular dwellings. *H. albicans* is likely so abundant because of its tolerance to disturbances; however, trunk diameter (about 10 cm), height (about 10 m), and wood properties (Brokaw *et al*. 2011) make this a suboptimal species for this kind of construction. Additionally, this plant species is intensively used in the Yucatan as firewood (Quiroz-Carranza and Orella 2010) and in recent years it has become very popular as a source of the pigments used on the inside of swimming pools (personal observation of authors); therefore, the population viability of *H. albicans* is expected to be compromised before too long. In the study area the availability of trees is in general decreasing due to deforestation. Land cover by secondary and mature forest has decreased from 41% to 28% (from 51,562 to 35,691 ha) in only ten years (1985–1995) and the rate is probably greater today (Sohn *et al*. 1999). Also, a reduction in the area of agroecosystems precludes the possibility of cultivating timber species. For some people the only choice is to buy the wood; however, to do so, people have to get salaried jobs outside of their community, which also results in the abandonment of traditional agroecosystems and the loss of construction knowledge (Sánchez-Suárez *et al*. 2017).

In conclusion, the gradual replacement of perishable plant materials by industrialized materials in the construction of vernacular dwellings in Sotuta is evident. The main reason behind this is the limited durability and availability of the natural materials. Traditional agroecosystems and their surroundings used to be primary sources of these materials, however landholding fragmentation and land use change have severely reduced their availability. The reduction in terms of the area of traditional agroecosystems is also influenced by cultural changes (transition from extended to nuclear families) and changes in socioeconomic variables (migration, expansion of the service sector of the Mexican economy). We suggest that there is a strong link between traditional agroecosystems and the use of local, perishable materials in vernacular dwellings. Despite material substitution, the vernacular dwellings of Sotuta maintain their shape and functionality; a relevant finding indicative of the high degree of resilience of vernacular dwellings in the study area and people's adaptation to new building materials. Previous studies identified traditional agroecosystems as hotspots of culture and agrobiodiversity (e.g., Galluzzi *et al*. 2010), however their value as reservoirs of traditional building materials has been overlooked. Major conservation efforts and resources have been allocated to forests, however, from a biocultural perspective, home gardens also provide important environmental services and play an important role in the conservation of traditions and ancestral management practices of plant resources.

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Informed Consent All informants gave verbal consent for the information they provided to be shared for academic purposes only.

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