Global Environmental Change 28 (2014) 141–152

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Unexpected climate impacts on the Tibetan Plateau: Local and scientific knowledge in findings of delayed summer

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ARTICLE INFO

Article history:
Received 7 October 2013
Received in revised form 13 February 2014
Accepted 17 March 2014
Available online 1 August 2014

Keywords:
Climate change
Local ecological knowledge
Tibetan Plateau
Phenology
Pastoralism

ABSTRACT

Knowledge of climate change and its impacts can facilitate adaptation efforts. However, complex system dynamics, data scarcity, and heterogeneity often generate both contradictory findings and unexpected climate change impacts. Here we present local ecological knowledge of climate and ecological change in central Tibet to support the finding of delayed summer on the Tibetan Plateau, a finding that has been subject to vigorous, ongoing debate based on Western scientific data. Tibetans who actively herd on a daily basis and are located at higher elevations were most likely to notice changes in seasonality, reported as later start of summer and green-up, and as delayed and shortened livestock milking season. Local meteorological data, indigenous observations of higher snowlines and long-term animal number data suggest that a regional warming trend, rather than land use change, may underlie the delayed phenology trends. We demonstrate that local ecological knowledge can reveal counter-intuitive outcomes and help resolve apparent contradictions through its strengths in situations of high variability, ability to integrate over a range of variables and time scales, and operation outside of Western scientific logic. This suggests local knowledge does not exist to be confirmed or disproved by Western science, but rather can also advance Western science and help contribute to its debates. It is precisely points of apparent contradiction within and between knowledge systems that are most productive for more extensive inquiry. Future research on climate change, and climate adaptation policy-making, will benefit from careful, contextual dialog with local observations, focusing on observable biophysical phenomena that are affected by temperature and precipitation and that are important to livelihoods.

1. Introduction

Knowledge of climate change and its impacts can facilitate adaptation efforts as it can guide policy makers to develop programs that reduce the adverse effects of climate change and that augment adaptive capacity (Seidl and Lexer, 2013). However, complex system dynamics, data scarcity, and differential climate changes and impacts across heterogeneous social–ecological systems can generate contradictory and unexpected findings, which can hamper adaptation efforts (Hoogstra and Schanz, 2008). The ongoing debate over spring vegetation phenological trends on the Tibetan Plateau, and the scientific disagreement over the role of climate change in driving these changes, illustrates the limitations of current scientific observations and knowledge of climate change and its impacts due to system complexity, heterogeneity and data scarcity.

Phenological changes associated with climate change have been widely documented and generally demonstrate an advancement of key events, such as green-up and flowering (Cleland et al., 2007; Rosenzweig et al., 2008). Changes in plant phenology have important implications for Earth system processes, including plant–animal interactions, hydrology, ecosystem carbon and

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http://dx.doi.org/10.1016/j.gloenvcha.2014.03.007
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energy balance, and the sustainability of livelihoods worldwide (Cleland et al., 2007; Wolkovich et al., 2012). Studies of phenology and climate change typically use satellite remote sensing (Yu et al., 2010), monitoring of atmospheric CO_2 (Keeling et al., 1996), and direct field observations of species over time (Cook et al., 2012) or under experimental climate change conditions (Arft et al., 1999; Cook et al., 2012; Dorji et al., 2013; Dunne et al., 2003). However, researchers have identified problems with these methods. For example, Wolkovich et al. (2012) examined 14 long-term, field-based observational phenology studies and 36 experimental phenology studies and found that for the same plant species, the experimental results were different in both magnitude and sign from the observational results. Moreover, the warming experiments under-predicted the timing of green-up by a factor of four compared to the long-term, observational studies. The authors attribute these mismatches to the complex interactions among multiple drivers within the long-term, field-based observations and to potential artifacts associated with the experiments. In a review of plant phenology and global change, Cleland et al. (2007) note that traditional statistical methods used to analyze ground-based studies fail to detect abrupt shifts in phenology. The authors also cite atmospheric interference and a paucity of biome-scale, ground-based, phenology data as problems associated with satellite-derived monitoring of phenology (Cleland et al., 2007). Rosenzweig et al. (2008) note that data on climate change effects on biological systems, as indicated by metrics such as phenology, are biased toward well-studied systems in North America and Europe.

Recent research about the phenology of vegetation on the important but understudied Tibetan Plateau has stirred an active and ongoing scientific debate. Through remote sensing of the Normalized Difference Vegetation Index (NDVI) from 1982 to 2006, Yu et al. (2010) found that beginning in the mid-1990s the spring phenology of the dominant meadow and steppe vegetation began to retreat, leading to a shorter growing season, despite continued warming. Statistical analysis revealed that warming spring temperatures advanced the growing season, but winter warming overwhelmed this effect, delaying spring phenology. The authors explain this phenomenon by later fulfillment of plant chilling requirements.

Three different published letters quickly challenged Yu et al.'s findings (Chen et al., 2011; Shen, 2011; Yi and Zhou, 2011). Using NDVI data from a different satellite that extended the dataset by three years and applying a different statistical analysis, Shen (2011) showed phenologic advance from 2003 to 2009 and demonstrated a link between phenology and spring, not winter, temperature for the time periods of 1998–2003 and 2003–2009. Yi and Zhou (2011) attributed the smaller NDVI values reported by Yu et al. not to delayed phenology, but to increasing atmospheric contamination in spring, as indicated by the Total Ozone Mapping Spectrometer aerosol index, which would affect the sensors' readings. Chen et al. (2011) suggested that factors other than temperature, such as grassland degradation, plant community shifts, and advances of freeze–thaw processes, could explain Yu et al.'s NDVI findings.

Subsequent work published by Piao et al. (2011) found no overall trend in green-up dates on the Tibetan Plateau from 1982 to 2006, while Shen et al. (2011) demonstrated delayed phenology over that timeframe. Both studies demonstrated an overall advancing trend from 1982 to 1999 and a delaying trend from 2000 to 2006, with high spatial variation in the results. For example, Shen et al. (2011) found overall advances in the eastern regions and delays in the central regions of the Plateau. Piao et al. (2011) found a greater magnitude of phenological changes at higher elevations, but cite 'large uncertainties' regarding change in spring phenology in Tibet. Their finding of recent decreasing spring temperatures at higher elevations further confounds the ability to generalize climate-phenology trends and relationships across Tibet (Piao et al., 2011). Both studies cite the need for more ground-based phenology studies on the Plateau. A more recent study that examined three different NDVI data products (Zhang et al., 2013) concluded that phenology has advanced over the past three decades, but questioned the quality of one of the commonly used NDVI data product (GIMMS) for the Tibetan Plateau over the measurement period used by Yu et al. (2010). There were objections to Zhang et al.'s findings based on reported trends in non-growing season NDVI (Shen et al., 2013) and decreasing snow cover trends (Wang and Chang, 2013), both of which could explain the spring increase in NDVI.

The ongoing scientific debate regarding whether plant phenology on the Tibetan Plateau is advancing or retreating (Chen et al., 2011; Shen, 2011; Shen et al., 2013; Wang and Chang, 2013; Yi and Zhou, 2011; Yu et al., 2010; Zhang et al., 2013) centers on the source, quality, and interpretation of the Normalized Difference Vegetation Index (NDVI) data derived from satellite images and neglects a crucial interlocutor in these debates: local ecological knowledge. The work reported here on Tibetan pastoralists' observations of environmental and climatic change demonstrates there is likely a warming-induced shortening of the growing season in the central Tibetan Plateau region of Nagchu Prefecture. We show how bringing local and scientific observations and knowledge into conversation is a complex and iterative process that requires understanding the cultural and livelihood contexts of indigenous peoples. Using changes in Tibetan Plateau seasonality, we demonstrate how this endeavor can be particularly illuminating in systems where climate–ecosystem relationships are complex and counterintuitive. We conclude that carefully contextualizing and evaluating findings within the strengths and limitations of both local ecological knowledge and scientific methods of observation and induction allows for new insights, particularly in understanding unexpected climate change impacts. These insights in turn can help plan for future climate change and aid in development of climate change adaptation policy, particularly at the local scale, where the effects of climate change have the most immediate impact on subsistence-based livelihoods.

2. Local ecological knowledge

Sustainability science researchers increasingly call for use of both local ecological knowledge (LEK) and Western science to help create a deeper understanding of climate change and its impacts (Alexander et al., 2011; Berkes and Berkes, 2009). A number of studies have demonstrated significant overlaps between local ecological knowledge and climate data gathered through scientific measurements (Alexander et al., 2011; Laborde et al., 2012; West and Vásquez-León, 2003). However, critical work in the social sciences informed by Science and Technology Studies and feminist standpoint epistemology suggests that sustainability science must move beyond simple comparisons, in which the role of local ecological knowledge is merely to be validated by scientific knowledge, a formulation that fails to recognize science as knowledge produced by socially situated actors (Agrawal, 1995; Alexander et al., 2011; Goldman, 2007; Goldman et al., 2011; Haraway, 1988; Harding, 1998; Turnbull, 2000). Here, we present results from complementary engagement between local ecological knowledge and Western science, which reduce overall uncertainty about climate change and its impacts. This analysis starts from the recognition that local ecological and Western scientific knowledge systems are both partial and situated; neither alone is a panacea for understanding and adapting to climate change (Agrawal, 1995; Berkes, 2007; Ostrom et al., 2007). Instead, it is necessary to search for possibilities that preserve both "liberatory elements of the enlightenment project and a wide diversity of other knowledge traditions" (Turnbull, 2000, p. 14).

We use the term local knowledge in this paper to refer to what is commonly also called traditional ecological knowledge (TEK; Berkes, 1999), indigenous knowledge, or indigenous environmental knowledge (Brosius, 1997; Ellen et al., 2000). We choose the term local ecological knowledge to stress that this knowledge is constantly changing, rather than static, as the terms "traditional" and even "indigenous" may be taken to imply. Like Western scientific knowledge, local knowledge is always in the making; it "undergoes continual generation and regeneration within the contexts of people's practical engagement with significant components of the environment" (Ingold and Kurttila, 2000, p. 192). Moreover, we use the term interchangeably with indigenous knowledge, with the understanding that the term indigenous itself is a political category, and that such knowledge is not limited to only peoples who are recognized as or identify themselves through the political category of indigeneity (De la Cadena and Starn, 2007; Li, 2000). In using local knowledge, we wish to signify what Raffles (2002) has also called "intimate knowledge": knowledge that is fundamentally relational, situated, and in process.

Critical work on other knowledge traditions has emphasized that differences are not absolute and that scientific knowledge is also 'local' in important ways (Agrawal, 1995, 2002; Latour, 1986). The problem of labeling contemporary practices of planting hybrid seeds or introduced cash crops as "indigenous" has led some scholars to propose "hybrid knowledge" as a more accurate term (Dove, 2002; Gupta, 1998). More radically, recognizing the need to place scientific and other knowledges in the same frame of analysis, some scholars have called for replacing an analytic of "knowledge" with one of "reason" (Lowe, 2006), or at least an insistence that all knowledge be understood as emplaced and processual. Thus, though we draw out a distinction between "scientific" and "local" knowledge, we do so with the caveat that in important ways, scientific knowledge is also "local" in the process of its production and in the bodily emplacement of its practitioners (Ingold and Kurttila, 2000).

Various knowledges become differentiated, however, through "the nature of the skilled practices through which [they] are generated" and through their relative abilities to travel through networks of power and hence to become abstract and apparently universal (Ingold and Kurttila, 2000; Latour, 1986; Raffles, 2002). Different sets of "skilled practices" produce different emphases, which become relevant in considering climate change. Western science typically concentrates quantitatively on a relatively small number of variables, relative to local ecological knowledge, which integrates information from a variety of system components that operate at different spatial and temporal scales and uses a large number of variables qualitatively to develop flexible mental models and interpretations. Local ecological knowledge systems have been cited as having distinct advantages, given their forms of skill and emplacement, in dealing with multiple variables and complexity, through a process similar to fuzzy logic governing expert systems (Berkes and Berkes, 2009).

Because the scientific emphasis in understanding climate change has largely been at the global level, local ecological knowledge can be helpful in adding local-scale observations, particularly where people are closely engaged with their environment through the continued practice of resource-based livelihoods. Indeed, where differences have been found between the conclusions of Western science and local ecological knowledge, they often have to do with the scale of observation of phenomena (Berkes, 2007; Reid et al., 2006). Local ecological knowledge can contribute to climate change adaptation through a variety of mechanisms, including understanding the implications of climate change for vulnerable groups and aiding NGO and government planning for adaptation efforts at local to national levels (Naess, 2013). Furthermore, exploring apparent discrepancies between and within scientific and local knowledge, where they arise, can lead to the identification of new mechanisms that might explain both sets of apparently contradictory observations, thereby creating new knowledge (Gearheard et al., 2010; Huntington et al., 2004). Indeed, we suggest that it is precisely these points of apparent contradiction both within and between knowledge systems that are most productive for discovery.

2.1. Local ecological knowledge and the Tibetan Plateau

The relative strengths of local ecological knowledge make it informative for assessing climate change and its impacts in remote, mountainous terrain such as on the Tibetan Plateau, where variability in climate and topography creates heterogeneity over short distances, and where rapidly changing biophysical and social drivers – such as climate and grazing management policy – result in complex system dynamics. Across the Tibetan Plateau, climatic conditions are highly variable, with mean annual precipitation ranging from more than 700 mm to less than 50 mm, and mean annual temperatures ranging from more than 6 °C to less than −10 °C (Schaller, 1998). Climatic conditions are also highly variable on seasonal, monthly, and daily time scales. Across the Tibetan Plateau, climate change is predicted to be several times greater than the global mean (IPCC, 2007; Nogues-Bravo et al., 2007; Xu et al., 2009), and there has been observed warming to date, though it has not been spatially uniform (Li et al., 2010; Liu and Chen, 2000). Furthermore, climatic observations on the Tibetan Plateau are based on data from relatively few meteorological stations, which tend to be biased in their locations along valley bottoms and near towns (Frauenfeld et al., 2005).

Pastoralism has been the predominant land use on the Plateau for millennia, with livestock stocking rates and herd composition (i.e., relative proportions of yaks, sheep and goats) exhibiting high spatio-temporal variability (Miller, 1999). Extreme events such as 'snow disasters,' which are large snowstorms where snow and ice persist on the rangelands and cause high livestock mortality, can generate large fluctuations in livestock numbers over time (Klein et al., 2011; Miller, 2000; Yeh et al., 2014). Differential implementation and enforcement of rangeland management policies focused on sedentarization, fencing and rangeland destocking (Bauer and Nyima, 2011; Miller, 1999, 2000; Yan et al., 2005; Yeh and Gaerrang, 2011), have further contributed to this land use heterogeneity and to the complexity of system dynamics.

Constraints due to altitude, infrastructure, and political sensitivities limit research access to the Tibetan Plateau, contributing to a paucity of ground-based data from this globally significant region. This partially explains the dominant focus on remote sensing efforts to understand phenology on the Tibetan Plateau to date (but see Dorji et al., 2013). However, given the significant climatic, land use and policy changes in the region, a field-based understanding of climate change, its impacts, and its interactions with other changing drivers, is especially important. To date, the only published studies of local observations of climate change on the Tibetan Plateau have come from herders in the southeastern part of the Plateau, in Yunnan province, where vegetation, topography, livelihoods, and thus the effects of climate change are all very different from those in the central plateau (Byg and Salick, 2009; Salick et al., 2012), and from farmers who rely on agricultural crops in central Tibet (Li et al., 2013).

3. Materials and methods

3.1. Study site

We conducted this study in Nagchu Prefecture, in the Tibet Autonomous Region of China (Fig. 1), a pastoral area of over 400,000 km^2 on the central Tibetan Plateau, with an average elevation of over 4500 m. We conducted interviews in four

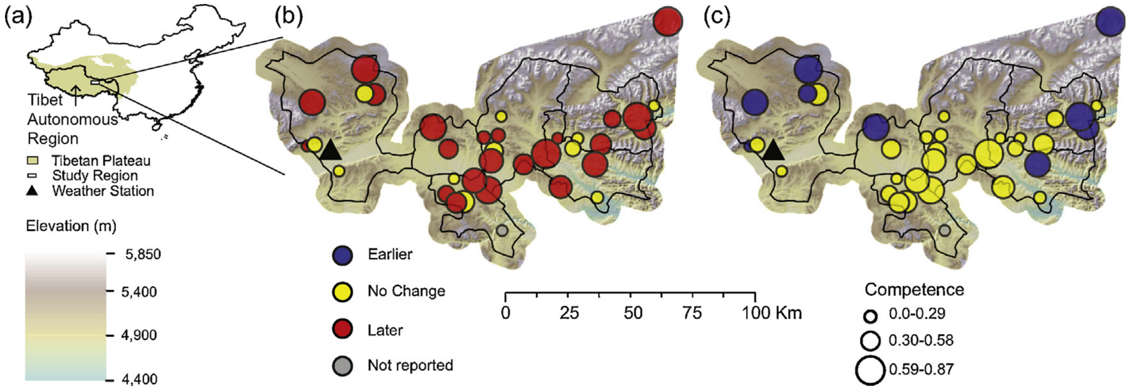

Fig. 1. Map of study region (a) and LEK observations of trends in the timing of the start (b) and end (c) of summer. For (b) and (c), each circle represents one respondent. The circle color indicates the type of change, while the circle size corresponds to each respondent's 'cultural competence' (see Section 3.2 of this paper). Larger circles indicate greater competence, or more consistent agreement with the dominant mental model of the group. The black triangle shows the location of the Nagchu meteorological station. The Amdo station is approximately 100 km SE of the Nagchu station.

townships of Nyenrong County (Sanglong, Sokshun, Nyenrong and Peshun) and two townships in Amdo County (Tardu, Panak), covering an area of 6732 km^2 with 2753 households. Most residents in these six townships make a living by raising yaks, sheep, goats and horses. In addition, over the past decade, some herders have earned considerable off-range income from harvesting and selling *Ophiocordyceps sinensis*, a caterpillar fungus with medicinal properties that is a highly valued commodity (Yeh and Lama, 2013). Other livelihood activities include business, salaried government work, and wage labor.

3.2. Interview data

We purposively interviewed residents in villages within each township to cover a broad geographic area, with the ideal interviewee being a knowledgeable local resident recommended by the village leader. In the summer of 2008, we conducted a total of 38 semi-structured interviews, with informants of a mean age of 52 (the oldest interviewee was 77 years old and the youngest was 33 years old). A native speaker conducted the interviews, which included basic questions about the household, livelihood strategies and sources of income, as well as local knowledge about climate and ecological change, in the local Tibetan dialect. We asked informants to comment about changes they have observed over their lifetimes. Previous work has demonstrated that pastoralists and farmers can reliably recall climate trends and extreme events over multi-decadal timeframes (Ovuka and Lindqvist, 2000; Sollod, 1990).

Although the Tibetan male interviewer attempted repeatedly to include women as respondents, they refused his requests saying they would be unable to answer questions, reflecting the culturally gendered domains of knowledge in Nagchu Prefecture. The number of interviews we conducted, comparable to those of other studies of local ecological knowledge of climate change (Gearheard et al., 2010), reflects the very low population density and transportation difficulties in this vast region. We analyzed the data using cultural consensus analysis (CCA), to examine shared knowledge about climate and ecological trends across households, and classification and regression tree (CART) analysis, to explore the variation in observed changes among respondents and the factors that contributed to the different observations. All names used in this paper are pseudonyms.

We coded the responses numerically and conducted CCA (Weller, 2007) using the Ucinet 6 software (Borgatti et al., 2002) to understand how perceptions and knowledge about climate and ecological change are shared among Nagchu herders. Cultural consensus theory arose in the field of cognitive anthropology as a tool to understand how knowledge and beliefs are shared within and between groups of people, and it is recognized as being well-suited to identifying shared sets of responses from purposively sampled interviewees (Crona et al., 2013). Increasingly, it is being applied in the context of natural resource management (Jones et al., 2011) to compare local ecological knowledge and scientific knowledge of resources (Miller et al., 2004) and to assess levels of agreement between and among diverse stakeholder groups (Atran et al., 1999; Stone-Jovicich et al., 2011).

CCA is a type of factor analysis that generates a quantitative measure of agreement about a particular topic across a range of questions. If most of the variability across respondents can be explained by a single factor, then their responses are considered to have a single, underlying set of answers that can be attributed to a shared "culture," in the sense of common beliefs, conceptions and mental constructs about the world (Romney et al., 1986). If the ratio of the first to second eigenvectors in the factor analysis is greater than three, this indicates that there is only one set of answers inherent in the data, meaning that heterogeneity in the responses is due to individual variation among people, rather than because fundamentally different sets of knowledge are held within the group (Weller, 2007). While this formulation of "culture" elides the presence of cultural politics and struggles over meaning, CCA is nevertheless useful as a tool for deducing commonly held knowledge and measuring degree of agreement among a particular set of respondents. Those who have more answers in common with the group are given higher "cultural competence" scores. These competence scores are used to calculate weighted frequencies for each response, such that those who tend to disagree with the dominant mental model of the group are given less weight in determining the agreed upon answers for the group. While this has the potential to devalue the responses given by people whose knowledge lies outside the group's dominant mental model, it also helps control for people who are guessing in their responses.

We analyzed responses about climate and ecology separately to ensure that each test of consensus pertained to only one domain of knowledge (Romney et al., 1986). We ensured that our sample size was greater than 29 respondents so that the model would correctly classify 99% of the responses at the 0.95 confidence level, assuming that respondents share at least 50% of their answers to the questions (i.e., have an average competence score of at least 0.50; Romney et al., 1986). Following Miller et al. (2004), we removed two interviewees who failed to respond to 10% or more of the questions in the ecology CCA and three interviewees in the climate CCA, leaving sample sizes of 36 and 35, respectively. Since the analysis cannot handle missing values, we randomly assigned responses to the remaining unanswered questions. These randomly generated responses are treated as "guesses" and corrected for in the consensus analysis (Weller, 2007). Initially, we analyzed yes/no responses separately from multiple-choice responses (e.g., temperatures are increasing/decreasing/not changing). We retained multiple choice answers in the analysis of ecological knowledge, but interviewees' multiple choice responses tended to be so divided on the direction of the climatic changes that we subsequently reduced them to yes/no answers about whether a given aspect of climate was changing or not, regardless of the direction of the change. Analyzing the data in this stepwise fashion allowed us to ascertain that respondents held a shared understanding of climate and ecological changes, while also elucidating the types of change with strong consensus and those for which responses were more heterogeneous and warranted further analysis.

One key question that was not part of the CCA was "How are permanent snowlines changing?" There were only 17 respondents who lived in areas with permanent snowline, a sample size that was too small to include in the CCA. Therefore, to assess the responses to the snowline question, and to compare the answers with other direct observations of climate change, such as observed temperature changes, we conducted a 2-way chi-square (χ^2) goodness of fit test (Rosner, 1995) on the count data, to assess whether the deviation between the observed individual responses and the expected responses due to chance (50% indicating one direction of change; 50% indicating the opposite direction of change) were statistically significant at $p \leq 0.05$. CCA and χ^2 goodness of fit analysis have different purposes and applications; these results are not directly comparable. Our paper relies on the CCA results and only employs χ^2 on a smaller sub-set of the data for the purpose of comparing different observations of climate change including the location of permanent snowline.

Consensus analysis serves as an important first step toward determining patterns of shared knowledge among Nagchu respondents, but it should not mask the value of individual responses as they vary with other factors, such as demographic conditions and location across the landscape. Furthermore, diversity of local ecological knowledge within a group can be an asset that should not necessarily be collapsed into a consensus view, particularly because this diversity may enhance the ability to adapt under uncertain and changing conditions (Ruelle and Kassam, 2011). To examine the variation in observations of change, and the possible factors that explain that variation, we conducted classification and regression tree (CART) analysis (Breiman et al., 1984) using the R package "rpart." CART uses binary recursive partitioning to successively split a dataset into increasingly homogenous subsets that are most strongly linked to an explanatory variable. For this analysis, we used the Gini rule for splitting, prior probabilities that are proportional to the observed data frequencies, and a loss matrix of 0/1. We identified factors reflecting geographic location, livelihood activities, and associated socio-economic status of respondents as potential variables that would influence perceptions of climate and ecological change. Geographic variables we included in the analysis were the respondents' summer household latitude, longitude and elevation. We included the average distance traveled annually while herding livestock as an additional variable in the CART analysis. The socio-economic variables we used in CART include the respondent's age, economic status (wealthy, intermediate, poor), likely exposure to news and radio (yes/no); whether the interviewee was a village leader (yes/no); whether the respondent's main livelihood was from herding (yes/no); the respondent's primary livelihood (herder, salaried worker, businessman, collector of caterpillar fungus, worker with multiple sources of off-range income), whether the interviewee made a primary living on or off the land (on-land would be through herding and collection of caterpillar fungus; off-land would be all other sources of livelihood listed above); and the monetary amount of government aid (loans) received.

3.3. Remote sensing, meteorological and livestock data

We characterized satellite-observed changes in phenology and productivity using the 8 km × 8 km GIMMS NDVI data acquired from the University of Maryland Global Land Cover Facilities site and the 250 m × 250 m MODIS Terra MOD13Q1 data product, acquired from Oak Ridge National Laboratories. For the MODIS data, we extracted mean indices for locations within a 10-km radius of the GPS household survey locations, which represents the average herding radius for our interviewed households. We used a 15-km radius for the GIMMS data, which are at an 8-km resolution, so that more pixels were represented in the analysis. We used TIMESAT to calculate season metrics, such as green-up and senescence, and integrals of greenness, which correlate with productivity (Jonsson and Eklundh, 2004). We conducted Mann–Kendall and seasonal Mann–Kendall tests to examine temporal trends in NDVI metrics and meteorological data from the Amdo and Nagchu weather stations. As individual, household-level NDVI values were not independent from each other (i.e., we observed spatial autocorrelation among households), we calculated an average yearly value across households and then conducted the Mann–Kendall trend test on the average values, which yielded a more conservative p-value as compared to conducting the analysis using all household values, as the latter analysis substantially inflates the sample size and constitutes pseudoreplication. The Mann–Kendall test is nonparametric and robust to non-normal distributions and outliers, which are common in time series of meteorological data (Hirsch and Slack, 1984). We also used this test to examine trends in livestock data over time for each of the six townships in our study region. For Tardu and Panak townships in Amdo County we have livestock number data (yak, sheep, goat, horse, all of which we converted to standard 'sheep units') from 1996 to 2009. For Nyerong, Sokshong, Songlong and Peshung townships in Nyerong County we have livestock number data from 1989 to 2009. For all of these analyses, we consider $p \leq 0.05$ to be statistically significant.

4. Results

Herders strongly observed changes in their environment during their lifetimes. For both the climate and ecological domains of knowledge, respondents shared a single, general mental model of these changes, as indicated by their CCA first to second eigenvector ratios that were greater than 3 (6.12 and 4.09, respectively). For the climate knowledge domain, respondents particularly noted changes in the timing and length of growing seasons. They observed changes in the length of both summers and winters, specifically indicating that summer is starting later, summers are shorter, and plant green-up is delayed (Table 1). For example, herder Wangdu, a 53-year-old village head in Sokshun Township, observed that winter has lengthened by about a month, spring is now cooler, longer, and arrives later, and summer is shorter and arrives later. Similarly, Drupgyal, a 45-year-old herder in Nyenrong Township, observed grass greening up about 15 days later over the past decade. He also observed that winter and spring have both become longer and colder, whereas the summer arrives later, is shorter overall and is marked by more temperature extremes than in the past. As Dawa of Sokshun Township put it, "It looks like one of the spring months is now a winter month." Many herders also commented on the delayed and shorter yak-milking season in recent years, as well as lower overall milk production. According to 63-year-old Tsewang of Peshun Township, in the 1960s, they were able to milk female yaks for three months, beginning in the fifth

Table 1
Culturally correct answers where a change was observed for climate and ecology knowledge domains as detected through cultural consensus analysis (CCA). These culturally correct answers were calculated using weighted frequencies within the CCA method. "Yes" column refers to % of 'yes' responses of total, unweighted responses; direction of response is % calculated from 'yes' responses. "–" indicates a broader question that had only a yes/no response.

Question[a]	Yes (%)	Direction (%)
Climate		
Snowfall trends changing?	51.35	–
Amount of snow in winter changing?	40.54	Increase (53.33)
Amount of snow in spring changing?	45.95	Decrease(70.59)
Winter climate trends changing?	70.27	–
Winter temperatures changing?	48.65	Decrease (66.67)
Length of winter changing?	43.24	Increase (93.75)
Timing of start of winter changing?	40.54	Earlier (93.33)
Summer climate trends changing?	81.08	–
Daytime summer temperatures changing?	48.65	Decrease (77.78)
Nighttime summer temperatures changing?	48.65	Decrease (72.22)
Length of summer changing?	54.05	Decrease (95)
Timing of start of summer changing?	67.57	Later (100)
Wind trends changing?	67.57	–
Number of windy days changing?	64.86	Increase (66.67)
Strength of wind changing?	54.05	Increase (80)
Ecology		
Vegetation quality changing?	62.16	Decrease (100)
Vegetation density changing?	70.27	Decrease (96.15)
Vegetation height changing?	72.97	Decrease (100)
Medicinal plant quality changing?	56.76	Decrease (100)
Medicinal plant diversity changing?	54.05	Decrease (100)
Plant phenology changing?	51.35	Later (100)

[a] Other questions we asked for which the culturally correct response was 'no change' were: *Climate variables* – snowfall (timing of start and end, frequency, variability, duration of snowfall at one time, accumulation, duration on ground); rain (change in trend, amount, timing of start and end, frequency, variability, duration, timing of lightning and thunder); winter (timing of end, temperature variability); summer (timing of end, temperature variability); wind (timing of start and end within a year and within a day, direction); ice and rivers (change in timing of freezing and melting); ground freezing, thawing (timing); hailstorms, hot spells, frost, fog (trends changing). *Ecology variables* – grass, shrub, palatable plant (amount); plant diversity; wetland quality; cracks in top-soil; erosion; springs (amount of water, number); river water (amount); insects, wolves, other wildlife (amount); pika numbers compared to pre '97/'98 snowstorm numbers.

(lunar) Tibetan month, but now yaks cannot be milked until the sixth month, and only for two months.

While local ecological knowledge of delayed summer and shifting seasonality presented a coherent model of change, the evidence for directly observed climate trends appeared contradictory. Respondents who inhabit lands with permanent snowlines observed snowlines receding and moving upslope, a strong indicator of warming, with 76% noting higher snowlines and 24% indicating no change ($p = 0.029$). However, when asked about temperature, most respondents cited no changes or decreases in temperatures (Table 1). Of those who noted temperature changes, 67% observed decreases in winter temperatures ($p = 0.16$), 78% observed decreased summer daytime temperatures ($p = 0.02$), while 72% observed colder summer nighttime temperatures ($p = 0.03$). Data from the closest meteorological stations (Fig. 1a) show gradual increases in annual temperature from 1971 to 2005, with an increase in annual temperatures of 0.25 °C and 0.43 °C per decade at the Amdo and Nagchu stations, respectively (Fig. 2a). Respondents did not consistently observe changes in precipitation (Table 1), while local meteorological stations showed an increasing trend of 10% per decade (Fig. 2b).

There was greater agreement on ecological conditions and change (average competence score of 0.68) as compared to the less homogeneous responses about direct climate phenomena (average competence score of 0.45; Fig. 3). Observed ecological changes included decreases in vegetation quality, density and height (Fig. 4a), and decreases in medicinal plant diversity and quantity.

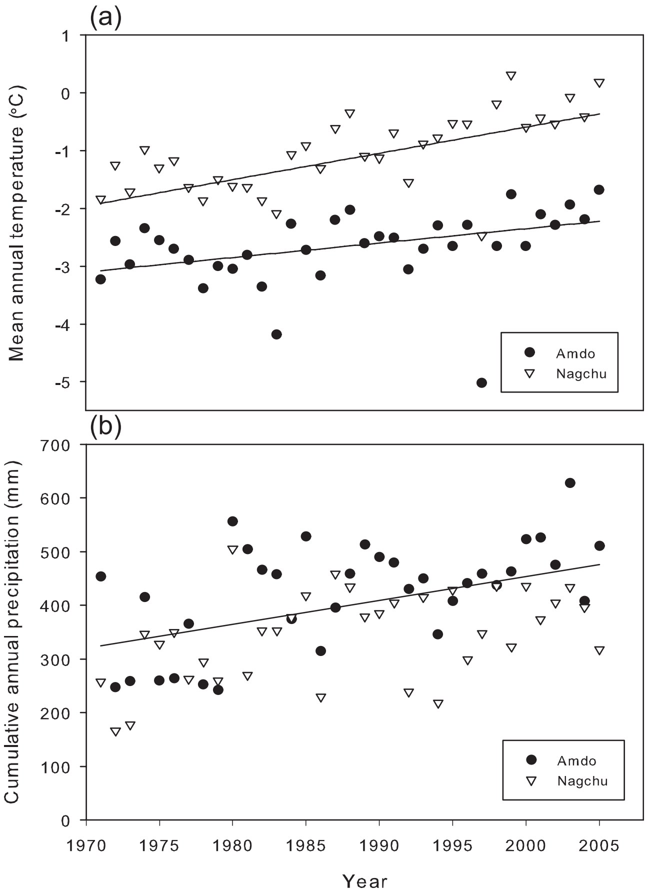

Fig. 2. Mean annual temperature (a) and cumulative annual precipitation (b) from Amdo (black circle) and Nagchu (open triangle) weather stations from 1971-2005 (see Fig. 1 for station locations). (a) For Amdo, Mann-Kendall (MK) tau = 0.36, $p = 0.003$; for Nagchu, MK tau = 0.53, $p < 0.0005$. (b) For Amdo, MK tau = 0.35; $p = 0.003$; for Nagchu, MK tau = 0.48; $p = 0.0001$. We only show one precipitation trend line since there was no difference between the two sites ($F = 0.0$, $p > 0.94$). Seasonal MK analyses yielded identical slope values as depicted above for annual means with adjusted p-values < 0.01.

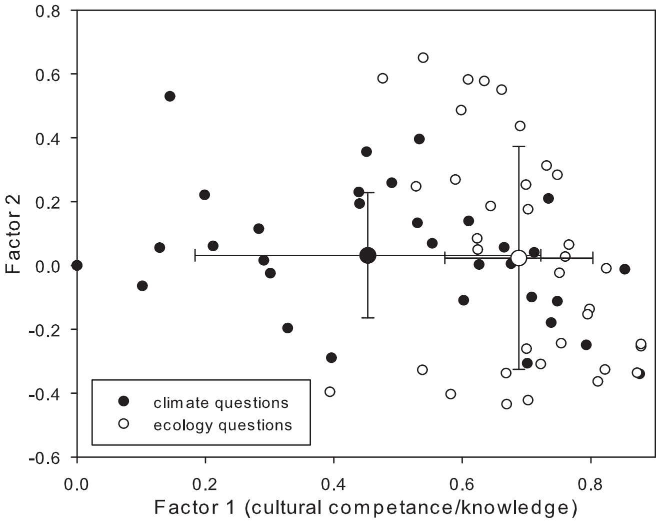

Fig. 3. Amount of cultural consensus on climate (black circles) and ecology (open circles) questions (see Section 3.2 in text). Smaller circles represent individual responses while the larger two circles represent the mean ± 1 standard deviation for factor 1 and 2. Higher average values on factor 1 represent greater shared knowledge or cultural consensus. Individuals with higher values in factor 1 have greater 'cultural competence' in that knowledge domain.

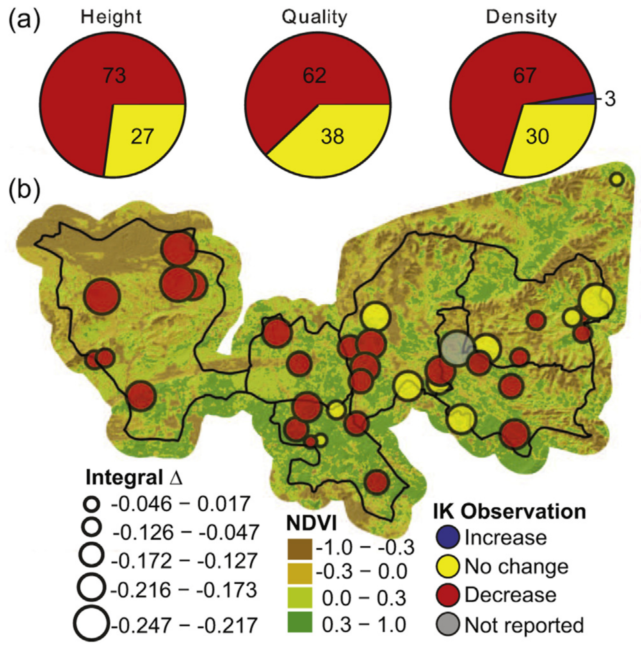

Fig. 4. Regional vegetation changes based on LEK observations and satellite NDVI. (a) LEK observations of vegetation height, quality and density changes ($n = 37$). Observations were significant (χ^2 result at $p < 0.05$) for all three vegetation indices. (b) Satellite observations of vegetation change. The size of the circle represents the amount of vegetation change (decrease) from 1982 to 2006 based on the GIMMS NDVI greenness profile integral (i.e., change in productivity) within 15 km of an interviewee's household location. The circle color indicates the LEK observation of vegetation height change. The background layer is the MODIS NDVI product from 7/26–8/5/08, when interviews were conducted.

The 25-year NDVI dataset similarly demonstrated a decrease in the integral of the greenness profile over time with a decreasing trend in 34 out of 37 household locations, indicating a regional trend of decreased aboveground vegetative production during that time period (Fig. 4b). This decrease in the NDVI integral could be caused by reduced length of the growing season during which vegetation is photosynthetically active, as well as by lower productivity via declines in vegetation health, which may be perceived as changes in quality, and decreasing biomass, which would be observed as changes in vegetation height and density.

CART results reveal that heterogeneity of respondents' observations of climate and ecological change within the general, shared, cultural models can be explained by patterns related to their livelihood, geographic location, and degree of mobility across the landscape. Those who observed the ecological and climatic changes described above tended to be people whose livelihoods were most directly derived from the rangelands, those situated at higher latitudes and elevations, and herders who moved further with their livestock. Respondents who were engaged in herding as their primary livelihood consistently observed summers starting later, whereas those mostly engaged in non-herding livelihood activities were split, with those in the higher latitudes (areas with generally more mountainous terrain and less vegetative production) observing delayed summers, and those in the lower latitudes (areas with generally less mountainous terrain and higher vegetative production) split between observing no change and delayed summers (Fig. 5a). Respondents living at higher latitudes also tended to observe delayed green-up (85% said delayed, $n = 13$) while those at lower latitudes were split with 65% observing no change and 35% noting a delay ($n = 23$, data not presented in Fig. 5 because there was only one split). Tibetans engaged primarily in herding or collection of caterpillar fungus, particularly those living at the higher elevations, reported shorter summers (Fig. 5b). Tibetans with greater mobility when herding livestock observed decreases in medicinal plant quality and diversity (Fig. 5c).

The 25-year (1982–2006) GIMMS NDVI record from our study region reveals no overall, statistically significant trend in phenology. We do observe delayed green-up and a shortening of the growing season (Fig. 6) that were not statistically significant, with a delay of 10.5 days (tau = 0.21, $p = 0.15$) and shortening of 17.2 days (tau = −0.21, $p = 0.14$) over the 25-year record.

The effect of the large and persistent snowstorm anomalies during the winter 1997/98 can be seen in Fig. 6a, where the extra soil moisture from the storms led to unusually early green-up in 1998. When this snowstorm anomaly year is removed from the analysis, there is a stronger trend with green-up 12.2 days later (tau = 0.25, $p = 0.08$); no significant change in senescence (8.6 days

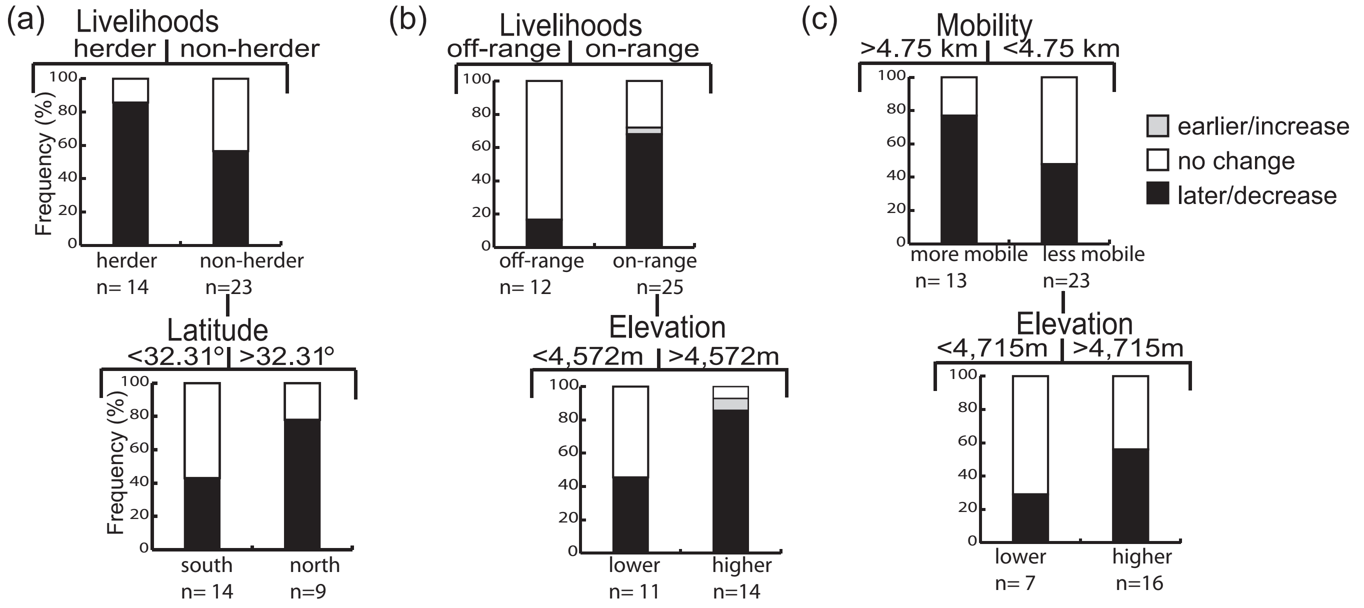

Fig. 5. Results from classification and regression tree (CART) analysis of LEK for (a) start of summer, (b) summer length and (c) medicinal plant quantity. All trees had two splits, with the primary split at the top and secondary splits below. Bar graphs illustrate respondents' observations within the groups identified by the CART analysis.

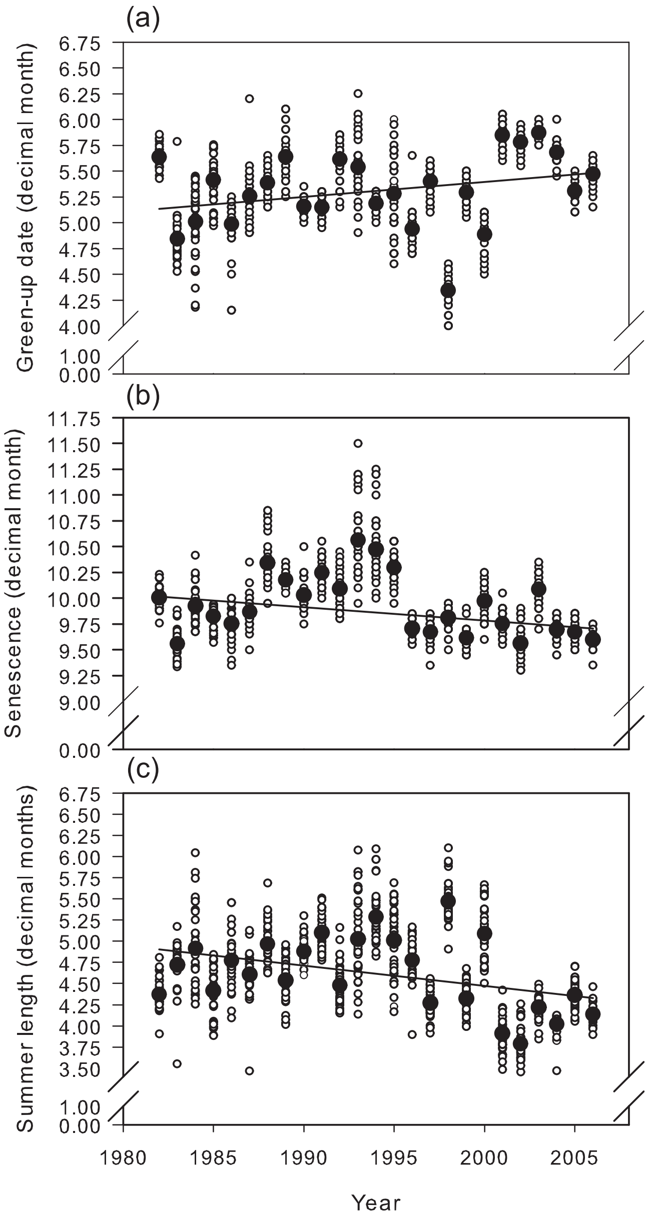

Fig. 6. Trends in (a) green-up date, (b) senescence and (c) length of summer based on the GIMMS NDVI dataset from 1982 to 2006. Each solid black circle represents a mean value for year ($n = 25$ years) averaged over all households. Smaller open circles show NDVI values within 15 km of each household GPS location. We conducted Mann–Kendall analyses on the average household data.

earlier, tau = −0.20, $p = 0.18$); and a trend toward decreased summer length of 17.8 days (tau = −0.26, $p = 0.08$) over the 25-year record. However, the GIMMS NDVI data over this time period should be interpreted with caution, due to changing sensors with different sensitivity to soil reflectance in 2000 (Gallo, 1998); but see (Forkel et al., 2013), and other potential issues that have been previously documented (Zhang et al., 2013). To be consistent with previous NDVI work on the Tibetan Plateau, we also examined the shorter-term records from the MODIS (2001–2011) and GIMMS (2001–2006) datasets from our study region. Here, the patterns were reversed, with advanced instead of delayed green-up, but the trends were not statistically significant. There was a non-significant advancing green-up trend of 9.9 days (tau = −0.31, $p = 0.21$) over the 11-year MODIS record and 11.5 days (tau = −0.60, $p = 0.13$) over the 6-year GIMMS record (Figs. 6 and 7).

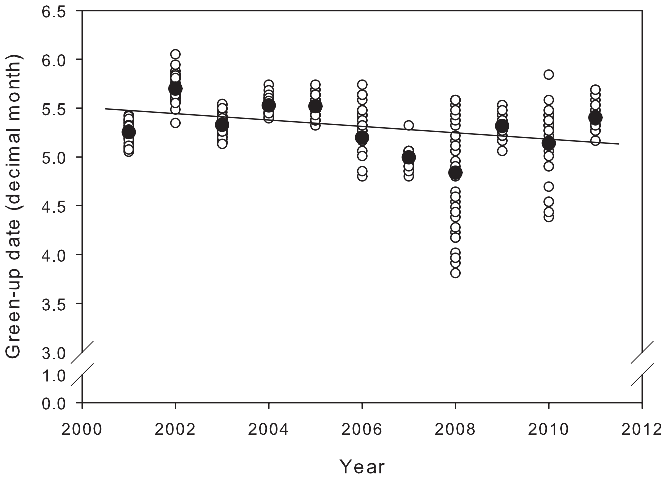

Fig. 7. Trends in green-up date based on the MODIS NDVI dataset from 2001 to 2011 using a Mann–Kendall trend analysis averaged across all households for each year ($n = 11$ years). Solid black circles represent a mean yearly value averaged over all households, while smaller open circles show NDVI values within 10 km of each household GPS location.

5. Discussion

Our findings demonstrate two specific ways in which local ecological knowledge can advance understanding of climate and ecological change. First, Western scientific data that record long-term trends can be subject to noise, spatiotemporal variability and short-term reversals. The 25-year GIMMS NDVI record from our study region revealed a trend of delayed green-up and a shortening of the growing season, but the more recent MODIS (2001–2011) and GIMMS (2001–2006) datasets show a shorter-term reversal of this trend. However, the quality of the GIMMS dataset over the measurement period has been questioned in this region (Zhang et al., 2013), and NDVI-based phenology studies of Tibet show opposing trends (Chen et al., 2011; Shen, 2011; Shen et al., 2013; Wang and Chang, 2013; Yi and Zhou, 2011; Yu et al., 2010; Zhang et al., 2013). The inherent integration of many qualitative observations and fuzzy logic of local ecological knowledge can be robust to these data idiosyncrasies: when asked about change over their lifetimes, Tibetans perceived delays in the start of summer over multi-decade timescales, despite the shorter-term reversal of this trend revealed by NDVI measurements. The longer-term NDVI trend toward delayed green-up corresponds with herders' local observations of shifts in seasonality, indicating that their long-term, qualitative perceptions support quantitative patterns deemed non-significant by Western scientific methods. Furthermore, while NDVI-based studies of phenological change on the Tibetan Plateau have sometimes found differing trends at broad regional scales (e.g., Piao et al., 2011; Yu et al., 2010), our finding that herders at higher elevations and in the more mountainous, less productive, northern part of our study region tended to more frequently report delays in the start of summer and shorter growing seasons, suggests that local ecological knowledge can provide information about climate and ecological change at finer scales, and highlight important aspects of landscape heterogeneity that can mediate environmental changes.

Second, Western scientific observations generally apply a top-down form of logic to observed correlations between climate changes and ecological responses. For example, climate warming that co-occurs with advancing phenology is in the 'direction expected' with warming and is often presented in a causal relationship (Rosenzweig et al., 2008). However, the complexity of ecological systems and processes can lead to counterintuitive relationships and surprising outcomes, such as delayed green-up with climate warming. Local ecological knowledge can provide independent observations of change that are not circumscribed by Western scientific logic and therefore can reveal these unexpected outcomes.

In contrast to the top-down logic of scientific observation, in which broad-scale climate change is expected to lead to local phenological change, Tibetan herders follow a bottom-up approach in which they interpret climate and its impacts through changes in livestock and grassland conditions. That is, herders' interpretations and observations of climate are made primarily through the conditions of their means of subsistence production (livestock) and the ecological conditions on which their livestock depend (rangeland condition), rather than directly as changes in temperature (Bollig and Schulte, 1999; Fernandez-Gimenez and Estaque, 2012; Marin, 2010). Furthermore, rapidly changing conditions, such as the unprecedented rate at which climate change is occurring and policy changes that suddenly alter management practices, may confound herders' understandings of climate-ecological relationships that have been formed based on past conditions (Fernandez-Gimenez, 2000). Their interpretations of environmental change are also likely underlain by a mix of cosmological and material explanations (Huber and Pedersen, 1997; Salick et al., 2012), which cause further divergence from a Western scientific interpretation of cause and effect between the climate and ecosystem.

While this bottom-up approach can make interpretation of drivers of change difficult, multiple lines of evidence suggest a link between climate warming and delayed phenology on the central Tibetan Plateau. The literature suggests that abiotic factors – such as light, temperature and snow – exert primary controls over alpine plant phenology in spring (Arft et al., 1999; Körner, 2003; Ram et al., 1988; Walker et al., 1999). The presence of a warming trend in our study region is supported by herders' observations of higher snowlines as well as data from the two closest meteorological stations in our research area, which show a gradual increase of annual temperature and precipitation, consistent with other studies that find a general warming and moistening trend on the Plateau (Li et al., 2010). Moreover, while both climate and grazing are key drivers of vegetation change on the Tibetan Plateau (Chen et al., 2011), the township-level livestock data suggest no significant directional changes in livestock sheep equivalent units (SEU) over two decades (1989–2009) in the four townships in Nyerong County and no change in Panak township in Amdo County over the 13 years (1996–2009) for which we have data. In Tardu, where we have 13 years of data, there was no significant change in total livestock numbers, but a significant increase in livestock SEU (35% increase in SEU over 13 years, $p = 0.003$, due to an increase in yak relative to sheep). However, we only had two respondents from this township, so this would not influence our results. Livestock management changes could also potentially affect phenology, but ethnographic research on pastoral practices in Nagchu shows that changes in management due to the Rangeland Household Responsibility System and other policies have been minimal there due to late and incomplete implementation (Yundannima, 2012).

Strong increases in minimum daily temperatures (Fig. 8) are consistent with the hypothesis that warming delays fulfillment of chilling requirements and phenology. However, results from experimental warming in central Tibet show that a warming-induced decrease in summer soil moisture delayed reproductive phenology of the dominant plant species (Dorji et al., 2013). This mechanism could also apply to delayed vegetative phenology and therefore suggests an alternative hypothesis, that vegetative phenology is delayed by changes in soil moisture associated with warming. Fig. 6 illustrates how large precipitation events (e.g., the snowstorms of 1997/98) can advance phenology through additions of soil moisture. Recent work examining spring phenology across China has highlighted relationships between precipitation, soil moisture and spring phenology (Cong et al., 2013; Wu and Liu, 2013). Shen et al. (2011) also found a relationship between pre-growing season precipitation and the onset of vegetative green-up for 32 of 50 sites on the Tibetan Plateau. Exploring the mechanism underlying the delayed vegetative phenology requires further direct examination, but the field-based study by Dorji et al. (2013) in any case fits with herder's observations of delayed summer.

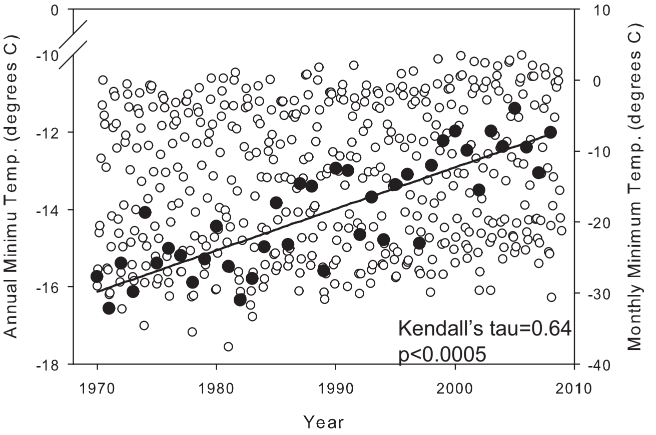

Fig. 8. Trends in annual (black circles) and monthly (open circles) minimum temperatures for the Nagchu weather station from 1970 to 2008. Data are from the NOAA Global Historical Climatology Network. The trend line presented is from Mann–Kendall trend analysis on the annual values; seasonal Mann–Kendall analysis on the monthly minimum data showed a similar slope with tau = 0.40, adjusted $p < 0.0005$.

Our use of LEK to help inform the scientific debate about phenology trends in central Tibet demonstrates how broadening the discourse to include non-scientific epistemologies can be illuminating. Our findings also illustrate how contradictions within and between knowledge systems can advance understanding of phenomena such as climate change. Specifically, the contradictions within LEK with reports of both higher snowlines and cooler temperatures; the contradictions between NDVI data sets and interpretations of phenology trends on the Tibetan Plateau; and the contradiction between herder reports of cooling with Western scientific agreement of an overall (though spatially heterogeneous) warming trend on the Plateau, provide an opportunity to explore these discrepancies and advance understanding in several realms.

We argue that the fact that herders did not report warming temperatures suggests that there has not been sufficient clarity in the sustainability science literature dealing with local ecological knowledge of climate change about what exactly is being observed as "climate." The growing literature on indigenous observations of climate change is based not on variables such as temperature and precipitation, but rather on observations of physical properties directly attributable to climate change, such as changes in sea ice (Laidler, 2006; Nichols et al., 2004) or sea level (Lefale, 2010). When examining less directly observable phenomena such as wind or weather persistence, observations have been much less directly correlatable to scientific data (Gearheard et al., 2010; Weatherhead et al., 2010). Small changes in average temperature are difficult for humans to observe directly, especially as temperature perception is affected by many factors including comfort, relative humidity and wind (Li, 2005; Strauss and Orlove, 2003).

This leads to several methodological observations about bringing local and scientific knowledge into conversation that are relevant to future studies on and beyond the Tibetan Plateau. First, changes in average temperature of the magnitude associated with climate change are of less direct significance to herders than changes in phenology and timing of livestock milking, factors of direct importance to herders' livelihoods to which they have a long history of being attuned. Unlike rangeland and livestock condition, upon which Tibetan herders frequently commented, their observations about changes in temperature were elicited only as a result of direct questions in interviews; it is not a topic of daily conversation. In other words, their knowledge about direct temperature change was produced much more directly through the process of interviewing itself. The subtle warming detected in meteorological data is not sufficient to be perceived directly by herders but affects vegetation phenology and confounds herders' bottom-up interpretation of temperature. That is, they may have extrapolated from the delayed phenology and decreased vegetative production that weather must be less favorable for growth and therefore colder, as stated in observations of cooler summers and longer and colder winters.

Secondly, direct perceptions of temperature are also likely confounded not only by increasing precipitation but also by changing patterns of shelter and clothing; in Tibet these include the recent transition from living in tents to houses and from traditional sheep-skin robes to manufactured clothing. Third, weather is a cultural phenomenon; it provides a framework for structuring and accessing memories, playing a metacognitive role (Strauss and Orlove, 2003). As a culturally specific way of organizing other kinds of memories, extrapolations about poorer (colder) weather are a logical way to articulate perceptions of grassland deterioration and poorer livestock conditions. Thus, the apparent contradiction in herders' observations of delayed summer and higher snowline, but cooler temperatures, can be understood through contextualization of local ecological knowledge in its culturally specific milieu and in relation to means of livelihood production.

Western science and LEK each have their strengths. For example, meteorological stations are better than people at detecting gradual changes in temperature. However, meteorological stations can only provide measurements at single points on the landscape, and previous findings of greater decreases in spring temperatures at higher elevations in Tibet demonstrate their inability to capture spatially heterogeneous trends (Piao et al., 2011). Local perceptions of cooler temperatures in our study region further underscore the need for more weather stations located in diverse terrain within Tibet, in order to increase confidence in the meteorological observations and their extrapolation across the Plateau (Piao et al., 2011). That is, it is possible that the meteorological data are not representative of what the herders are experiencing, as the climate stations are biased toward valley bottoms and are relatively far from where people are living and conducting their rangeland-based livelihood activities.

6. Conclusions

While there have been many observations of warming-induced, advanced green-up in different systems and regions of the world (Cleland et al., 2007; Menzel et al., 2006; Root et al., 2003; Rosenzweig et al., 2008), our findings support the finding of delayed onset of the summer growing season on the central Tibetan Plateau. We suggest that an approach that accesses local knowledge across Tibet, combined with Western science approaches, will be the most productive way to resolve the phenology debate, which to this point has been narrowly focused on Western scientific data. We highlight that the role of local knowledge is especially valuable in this debate given the particular challenges posed by the Tibetan landscape and by remote and heterogeneous mountainous terrain more generally. More studies of LEK of environmental change across the Tibetan Plateau will further illuminate the complex changes in this region and the implications for the people who reside there.

Our work confirms that people who move across a heterogeneous landscape in pursuit of resource-based livelihoods are critical sentinels of climate change and its impacts, particularly in remote and mountainous terrain, where climate and ecological change are variable and where Western scientific data are sparse. Rural Tibetans who are actively herding on a daily basis were most likely to notice changes, reported as later green-up and start of season and as delayed and shortened milking season. Their close observations of these ecological elements grow out of a long history of observing the placement of the Sun, Moon, and Stars in relation to local topographical elements, to track cyclic events important to their pastoral livelihoods (Belezza, 1997). This attention makes them particularly well attuned to identifying changes in the timing and duration of the seasons that they observed. The importance of mobility is highlighted by the fact that those who moved further with their livestock were most observant of key ecological changes related to medicinal plants, which are important to livelihoods and physical well-being.

Our findings demonstrate that local ecological knowledge can participate in the adjudication of scientific debates by supporting certain claims and helping to resolve apparent contradictions. It does so through its strengths particularly in situations of high variability and with its ability to integrate over large numbers of variables over longer time scales and its operation outside of Western scientific logic. In particular, local ecological knowledge provided significant support for the finding of delayed start of summer on the central Tibetan Plateau (Yu et al., 2010) that corresponds with an on-going regional warming trend. Exploring apparent discrepancies within and between Western science and local ecological knowledge, where they arise, can lead to the identification of new mechanisms that might explain both sets of apparently contradictory observations, creating new knowledge (Gearheard et al., 2010). Both future scientific research and climate adaptation policy-making will benefit from careful, contextual dialog with local ecological knowledge, focusing on observable biophysical phenomena that are affected by climate and important to livelihoods.

Acknowledgements

We thank D. Tsering for conducting fieldwork, J. Snodgrass for help with CCA, D. Ojima for his assistance, the Tibetans in Nagchu and Amdo for their contributions to this project, and three anonymous reviewers for their improvements to the manuscript. This work was supported by NSF SBE-0624315.

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