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The collapse of ancient societies such as the Mesa Verde-region pre-Hispanic Pueblos has puzzled generations of scientists. Many explanations for particular cases have been suggested, from combinations of social, political and economic factors (Tainter 1988), to climatic factors such as drought. Here we propose a new hypothesis, suggesting why precisely societies that invested in impressive structures became vulnerable to disturbances. Empirical evidence shows that humans have a strong tendency to hold on to previous investments even if this is a rationally bad choice. We argue that this leads to a tendency not to abandon settlements if much has been invested in them, even if resources become scarce. We use a stylized model to illustrate under which conditions sunk-cost-related collapse

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is likely, and present archeological evidence that sunk-cost effects may be important in explaining the delayed demise (relative to hamlets) of pre-Hispanic Puebloan villages in the face of resource stress.

Various studies suggest that the collapse of many ancient societies with obvious architectural remains coincides with unfavorable climatic events such as droughts (Hodell et al. 1997, 2001; Weiss and Bradley 2001). However, a puzzling question remains whether some common aspect of societies such the Classic Maya and (on a smaller scale) the pre-Hispanic Pueblos that built large structures made them especially vulnerable to such collapse. Indeed, Tainter (1988) has suggested such an underlying pattern. He proposed that increasing complexity makes societies fragile. As the complexity of a society increases, investments in resource extraction, administration, organization and defense increase. Increase of complexity is initially favorable but over time rates of return to investments decrease. Taxes and other costs rise while benefits do not increase proportionately. Eventually, a society will reach a point beyond which the increase of complexity leads to negative returns, breeding disaffection and making the society liable to collapse.

Here, we propose an alternative (or at the very least, contributing) cause for the collapse of ancient societies, based on a well documented systematic deviation from rational decision making known as the ’sunk-cost effect’ (Arkes and Ayton 1999). Economic reasoning tells us that prior investment should not influence one s choice between options. Only the expected future costs and benefits of the current options should influence one s decision. However, numerous studies (Arkes 1996; Arkes and

Ayton 1999; Teger 1980) show that humans do consider prior investment in deciding what course of action to take.

Most sunk-cost research is focused on individual decision making. The main explanation of observed escalation of commitment is self-justification (Brockner 1992). The idea of self-justification is that people do not like to admit that their past decisions were incorrect, and therefore reaffirm the correctness of those earlier decisions even in the face of evidence that the outcome was unsuccessful. One would expect that such irrational behaviour could be corrected in groups. However, groups actually tend to make riskier decisions than the mean of decisions made by individuals (Bazerman et al. 1984). Empirical studies suggest a general hysteresis in public opinion which tends to remain resistant to change and then suddenly shift to another opinion (Gladwell 2000). This may be largely due to a general tendency of individuals to agree with peers as demonstrated in classical experiments (Asch 1955). Moreover, a typical goal for political decisions in small-scale societies is to reach consensus (Boehm 1996). Once members of a group reach consensus, the easiest way to maintain consensus is to stay committed to the group s decision (Janis 1972). Thus even when the group is faced with negative results, members may not suggest abandoning an earlier course of action, since this might break the existing unanimity.

In conclusion, there is abundant empirical evidence that humans become increasingly unlikely to abandon a (failing) course of action to the extent that they have more existing investment in it, and that this effect tends to be amplified by group processes. We propose that this dynamic may lead to the postponing of small adaptive adjustments until more dramatic changes become necessary. To see how this effect might lead to collapse of settlements, suppose that the dynamics of the local renewable resources (R) used by a settlement of humans (H) can be described by a classic model of logistically regrowing resource exploited by a consumer such as:

$$\frac{dR}{dt} = g\,R\,(1 - \frac{R}{K}) - c_{\max}\,\frac{R}{R + h_R}\,H + i \tag{1}$$

Where g is the maximum growth rate and K the maximum level of the resource, c_{max} the maximum per capita human resource consumption, and h_R the resource level needed to reach 50% of the maximum consumption rate. A small diffusive resupply of local resources (i) from neighboring areas is not essential but may prevent irreversible extinction of local resources (Scheffer and de Boer 1995). If consumers in such models are efficient exploiters (h_R small relative to K) the equilibrium resource level will be a sigmoidal function of the population size of humans (fig. 1) as described for instance for various exploited ecosystems (Scheffer et al. 2001). In our case it implies that over a range of human population densities two alternative stable states are possible: one with a relatively high resource level on the upper branch, and an alternative overexploited state with a low resource level at the lower branch. The dashed middle section represents unstable equilibria that mark the critical resource level below which recovery is impossible.

We will not consider human population dynamics in detail, but simply assume that the population in the settlement tends to grow if resources are abundant, but decrease if the resource level falls below a certain critical limit (R_C) when individuals quit the settlement in search of better opportunities. We may now analyze the dynamics graphically through a slow-fast approach (Rinaldi and Scheffer 2000), if we consider the dynamics of the dynamics of human settlement size (H) to be slow relative to the dynamics of the resource. This is certainly a reasonable assumption for many agricultural societies where production may vary greatly from year to year; pre-Hispanic Pueblo dry-farming regimes of southwestern North America provide especially good examples (Van West 1993).

Plotting the critical resource level (R_C) below which humans quit the place together with the resource equilibrium curve we can explore the expected effect of investment in fixed structures (either temples, other public structures, or housing) on the dynamics of settlements (fig. 2). The sunk-cost effect implies that the critical resource level (R_C) tolerated before abandoning the site should decrease if more has been invested in fixed structures. Thus, if not much has been invested in local settlements this level will tend to be high (fig. 2a) resulting in a stable equilibrium at the intersection of the two zero-growth isoclines. If sunk-cost effects cause people to leave only at a lower resource level this equilibrium shifts to higher population densities (fig. 2b). At even stronger sunk-cost effects the intersection is in the unstable part of the resource curve (fig. 2c). In this case the settlement will grow until point F_2 is reached and the resource crashes, followed by abandonment of the settlement. Eventually the resources will recover and new settlements may be set up in the same area, or nearby, resulting in a cyclic development.

Obviously, conditions are never constant. The effect of adverse events in our model can most intuitively be visualized by means of stability landscapes (fig. 3). Stochastic events that reduce resource abundance (e.g., pests, fires, droughts) may have little effect in small settlements but can easily bring the system across the border of the attraction basin of the over-exploited state in large settlements resulting in a crash. Thus the model predicts that sunk-cost effects can lead to growth of settlements to a point where they are about to overexploit their resources. At this point resilience (’the basin of attraction’) becomes very small and adverse stochastic events will tend to induce a collapse of large settlements.

Evidently, the actual value of the parameters in such abstract models will be difficult to assess in practice, but analyses with various minimal models of this form (not shown) indicate that the behavior occurs over a wide range of parameter values and alternative models. For instance, we analyzed an alternative model in which human dynamics are included explicitly and the critical point for leaving a settlement depends on realized consumption (C) rather than resource level (R). This yielded the same qualitative results. Also, we obtained similar results from a more elaborate model including the economics of societies and the dynamics of investment in settlement structures (Janssen et al. 2002). It thus appears that the prediction is quite robust against details of the models used: societies that invest heavily in structures, monuments, or even equipment and facilities for very specific extractive activities become liable to collapse through sunk-cost effects from resource overexploitation.

The predictions of this hypothesis should be examined against the archaeological record. Here we briefly discuss evidence from the pre-Hispanic Pueblo (Anasazi) who constructed some of the largest non-earthen structures built in the U.S. before the Chicago skyscrapers of the 1880s (e.g., Pueblo Bonito, Chaco Canyon, New Mexico; Lekson 1984). In the U.S. Southwest, the Anasazi constructed very many hamlets and small villages, but also some large settlements which frequently have evidence of large and labor-costly "public" structures such as great kivas, over-sized pithouses, D-shaped and other multi-walled structures, enclosing walls, and so forth, lacking at small sites. The case is especially suitable for testing for sunk-cost effects, because tree-ring analysis can frequently provide estimates of potential annual agricultural production, as well as high-resolution dating of construction activity in both small and large settlements. The sunk-cost hypothesis predicts that people will continue to invest in construction at large settlements even into periods of scarcity, whereas construction at small settlements should be confined to periods of relative abundance.

The area near the town of Dolores in Southwest Colorado was intensively studied by the Dolores Archaeological Program from 1978-1985 (Breternitz et al. 1986). Most of the numerous Puebloan sites in this area date to between A.D. 650 and 900. Two obvious classes of residential sites existed: hamlets of one or a few households, and villages of a dozen or more, and in one case nearly 200, households. In fig. 4 (top) we graph construction timber procurement events (Schlanger and Wilshusen 1993) against a standardized proxy measure for agricultural productivity. As predicted by the sunk-cost effect, construction in hamlets is restricted primarily to years in which productivity is at or above the long-term mean, whereas construction in villages persists under highly variable conditions. By the end of the occupation in the late-A.D. 800s there is evidence of depletion of wood resources, piñon seeds, and animals (reviewed by Kohler 1992). Following the collapse of these villages, the Dolores area was never reoccupied in force by Puebloan farmers.

A second similar case comes from nearby Sand Canyon Locality west of Cortez, Colorado, intensively studied by the Crow Canyon Archaeological Center over the last 15 years (Lipe 1992). Here the main occupation is several hundred years later than in Dolores, but the patterns of construction in hamlets versus villages are similar (fig. 4, bottom). The demise of the two villages contributing dated construction events to fig. 4 (bottom) coincides with the famous depopulation of the Four Corners region of the U.S.

Southwest. There is strong evidence for declining availability of protein in general and large game animals in particular, and increased competition for the best agricultural land, during the terminal occupation (reviewed by Kohler 2000).

We draw a final example from an intermediate period. The most famous Anasazi structures, the "great houses" of Chaco Canyon, may follow a similar pattern. Windes and Ford (1996) show that early construction episodes (in the early A.D. 900s) in the canyon great houses typically coincide with periods of high potential agricultural productivity, but later construction continues in both good periods and bad, particularly in the poor period from ca. A.D. 1030-1050. Unfortunately, there are very few cutting dates available for comparison from the contemporaneous small sites in the canyon.

For one of these cases there is an alternative explanation for continued investment in large sites during bad times. Widespread violence during the late thirteenth century A.D. occupation of the northern Southwest (Kuckelman et al. 2000) may have made life in hamlets simply too dangerous. However, the commonality of the patterns expected under the sunk-cost effect where no alternative explanation seems satisfying, strongly suggests that this mechanism operated in the histories of pre-Hispanic Puebloan societies.

Certainly, more archeological records would need to be scrutinized to explore the generality of the sunk-cost explanation for the vulnerability of prehistoric societies with large structural investments to collapse. However, the strong empirical foundation in social psychological work, and the remarkable fit to the Puebloan data are encouraging. An attractive aspect of the theory is that despite its simplicity it covers the three major ingredients that have been reappearing in the literature for decades: the role of adverse events, the impressive size of collapsing settlements and signs of overexploitation of resources during terminal occupations.

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Fig. 1. Equilibrium level of local renewable resources (R'=0) as a function of human population size in a settlement. Three alternative equilibria exist for population densities between F_1 and F_2. Equilibria on the dashed middle section are unstable and represent the border between the basins of attraction of the two alternative stable states on the upper and lower branches. If resource levels are high (on the upper branch) but the human population grows beyond the bifurcation point F_2 the resource collapses to the over exploited state. From there it will only recover if the human population falls below the other bifurcation point (F_1).

Fig. 2. The critical resource level (R_C) below which the human population in a settlement declines defines the zero-growth isocline (H'=0) of the settlement. Assuming human dynamics to be slow relative to those of resources we analyze the stability of the equilibria at intersections with the resource isocline (R'=0). (a) In the absence of sunk cost effects, R_C may be relatively high resulting in a stable equilibrium (*E*). (b) If sunk-cost effects cause people to leave a settlement only at lower resource level the equilibrium (*E*) shifts to higher population densities close to the bifurcation F_2. (c) At even stronger sunk-cost effects the intersection occurs in the unstable part of the resource curve. In this case the settlement will grow until point F_2 is reached and the resource crashes, followed by abandonment of the settlement. After the resources recover a new settlement may be set up resulting in a cyclic development.

Fig. 3. The bottom plane shows the equilibrium curve as in Fig. 2. The stability landscapes depict the equilibria and their basins of attraction at five different conditions. Stable equilibria correspond to valleys, the unstable middle section of the folded

equilibrium curve corresponds to hill tops. At large population sizes the attraction basin becomes small and an adverse event (1) may induce a complete collapse of resources through overexploitation. By contrast, in small settlements a similar event (2) will have only moderate effects.

Fig. 4 *(Top)* Timber procurement events (TPEs) (Schlanger and Wilshusen 1993) reconstructed from wood recovered from structures in the Dolores Archaeological Program area, graphed against proxies for agricultural production derived from tree rings and smoothed to the mean of the current year plus the previous two. Wood from small hamlets (H) has only been harvested in relatively productive years whereas construction in the large villages (V) apparently continued into periods of poor agricultural production. The two villages contributing dated construction events are Grass Mesa (Lipe et al. 1988) and McPhee (Kane and Robinson 1988) and standardized tree-ring indices from Petersen (1987) were used. *(bottom).* TPEs in the Sand Canyon Locality area, graphed against standardized estimates of local potential agricultural productivity derived from tree rings by Van West (1993) and smoothed to the mean of the current year plus the previous two. The two villages contributing TPEs are Sand Canyon Pueblo (Bradley 1992) and Castle Rock Pueblo (Kuckelman 2001); hamlet construction data are from Varien (1999). In both panels, the dotted lines connecting TPEs from the same sites do not necessarily indicate continuous occupation and do not track production between TPEs.

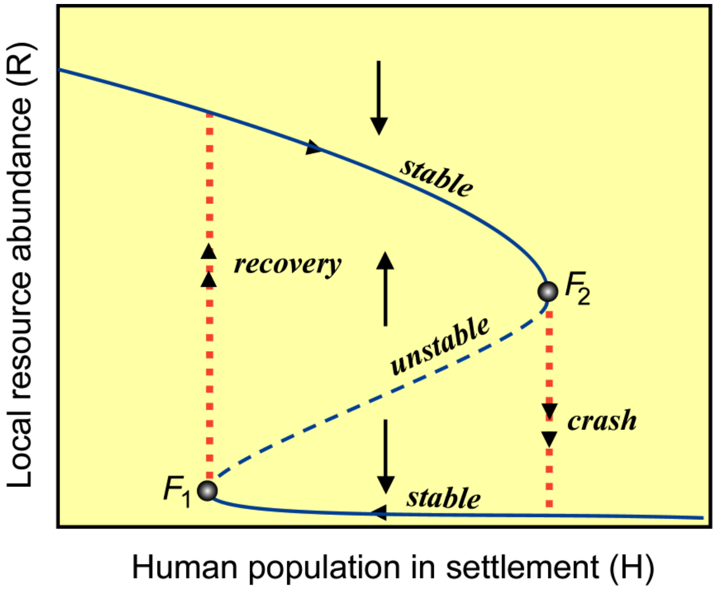

Local resource abundance (R)
Human population in settlement (H)
stable
recovery
F_2
unstable
crash
F_1
stable

Fig. 1

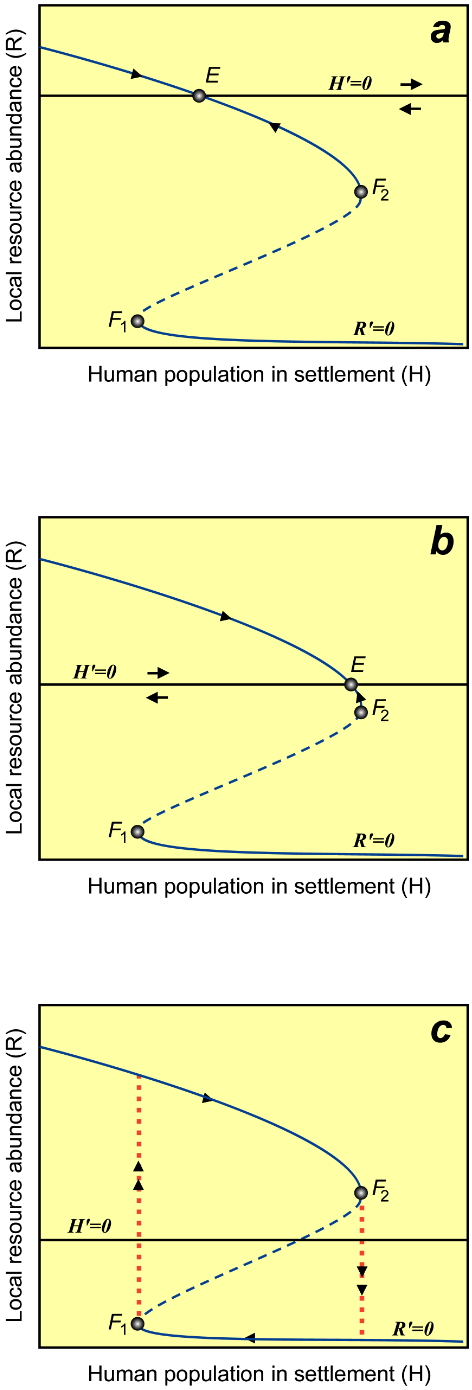
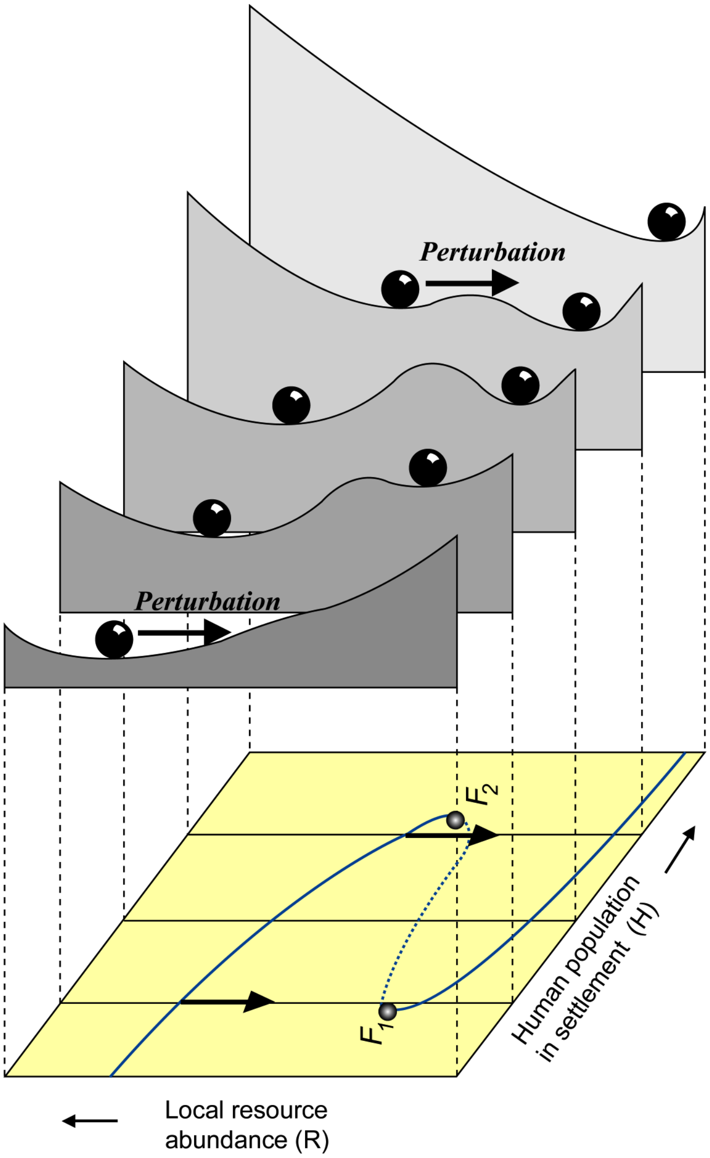
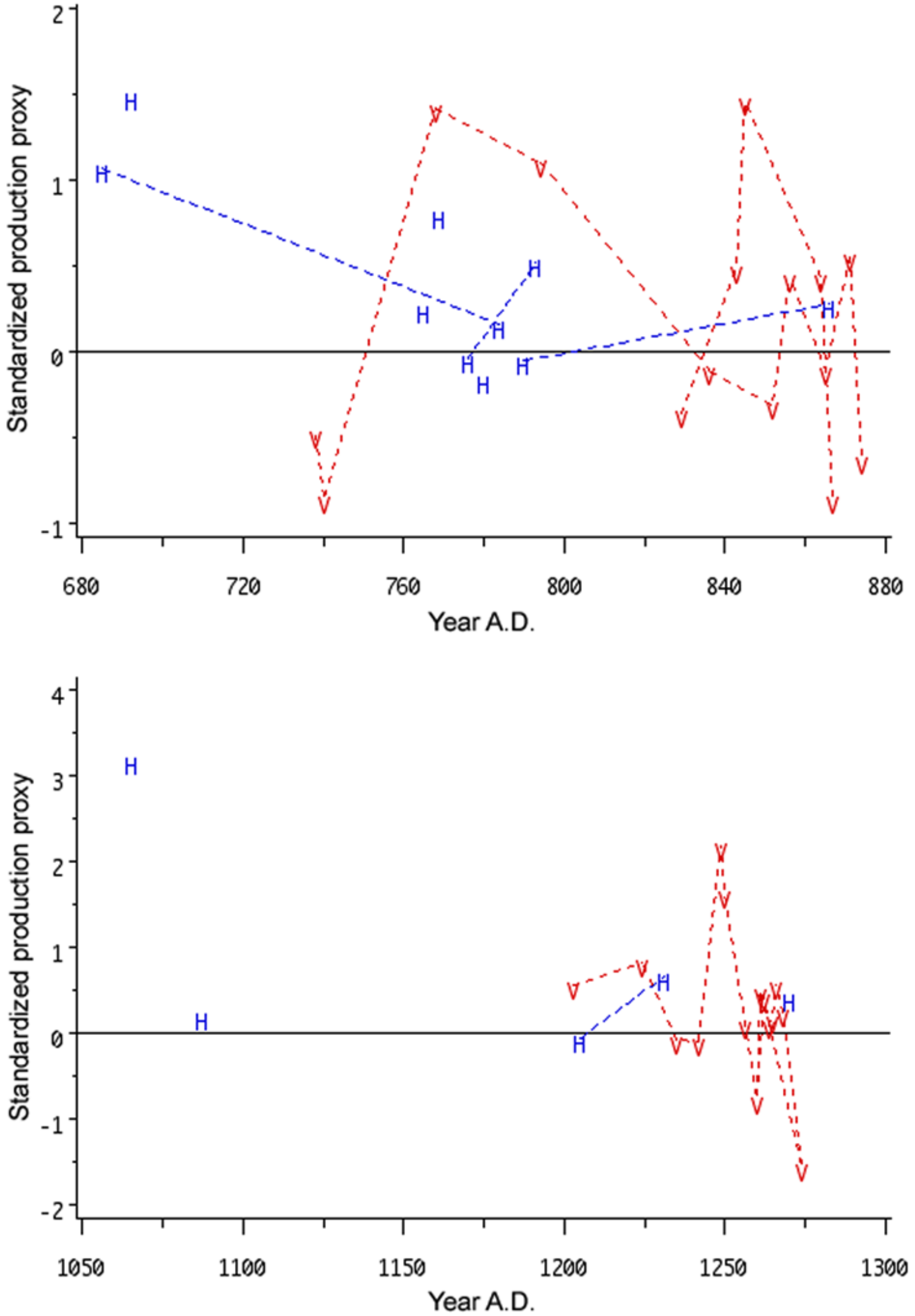

a
E
H′=0
F2
F1
R′=0
Local resource abundance (R)
Human population in settlement (H)
b
H′=0
E
F2
F1
R′=0
Local resource abundance (R)
Human population in settlement (H)
c
F2
H′=0
F1
R′=0
Local resource abundance (R)
Human population in settlement (H)

Fig. 2



Perturbation
Perturbation
F_2
F_1
Human population in settlement (H)
Local resource abundance (R)

Fig. 3



Standardized production proxy
2
1
0
-1
680
720
760
800
840
880
Year A.D.
H
V
Standardized production proxy
4
3
2
1
0
-1
-2
1050
1100
1150
1200
1250
1300
Year A.D.

Fig. 4