PNAS | RESEARCH ARTICLE | SUSTAINABILITY SCIENCE | OPEN ACCESS

Evolution of system connectivity to support food production in the Indus Basin in Pakistan

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Edited by Arun Agrawal, University of Michigan-Ann Arbor, Ann Arbor, MI; received March 6, 2023; accepted March 4, 2024

Sustainability challenges related to food production arise from multiple nature-society interactions occurring over long time periods. Traditional methods of quantitative analysis do not represent long-term changes in the networks of system components, including institutions and knowledge that affect system behavior. Here, we develop an approach to study system structure and evolution by combining a qualitative framework that represents sustainability-relevant human, technological, and environmental components, and their interactions, mediated by knowledge and institutions, with network modeling that enables quantitative metrics. We use this approach to examine the water and food system in the Punjab province of the Indus River Basin in Pakistan, exploring how food production has been sustained, despite high population growth, periodic floods, and frequent political and economic disruptions. Using network models of five periods spanning 75 y (1947 to 2022), we examine how quantitative metrics of network structure relate to observed sustainability-relevant outcomes and how potential interventions in the system affect these quantitative metrics. We find that the persistent centrality of some and evolving centrality of other key nodes, coupled with the increasing number and length of pathways connecting them, are associated with sustaining food production in the system over time. Our assessment of potential interventions shows that regulating groundwater pumping and phasing out fossil fuels alters network pathways, and helps identify potential vulnerabilities for future food production.

modeling for sustainability | Human-Technology-Environment (HTE) framework | food production | Indus River basin | network centrality

Understanding the long-term dynamics of interactions among humans, technologies, and the environment is a vital challenge for sustainability analysis. One example of this is seen in the case of global food production, which increased in the past century, aided in part by technological innovation (1). Simultaneously, adverse regional environmental impacts, including loss of biodiversity, degradation of ecosystems, pollution of water, and soil salinization highlight prevailing methods of agricultural production that are not sustainable (2). The history of the Indus River basin (IRB), home to one of the oldest human civilizations (3), illustrates the challenge of analyzing factors that mediate observed outcomes in long-term sustainability-relevant objectives such as crop production. Since Pakistan's independence in 1947, its population has grown from ~38 million in 1950 to an estimated 230 million in 2021. Ten "exceptionally high floods" (4) occurred during 1947 to 2022, resulting in major life and property losses. Political disruptions in Pakistan have been frequent, including partition of Indus basin land and water resources, major military conflicts, and oscillation between centralization and decentralization of federal, provincial, and local governance. Given these disturbances, one might expect high volatility or even episodes of collapse of food production leading to famine, as occurred periodically in precolonial and colonial times (5, 6), but this has largely not occurred. Aggregate food production in the Punjab region studied here, which is an important part of broader food security overall, has trended upward in the last 75 y (Fig. 1 and *SI Appendix*, Fig. S1).

While food production has been sustained, several trends raise broader sustainability challenges. An estimated ~21% of children under 5 are moderately or severely underweight and ~32% are moderately or severely stunted (*SI Appendix*, section S1), highlighting a persistent lack of access to nutritious food. Extensive water withdrawals from the Indus and its tributaries have led to riverine ecosystem degradation and pockets of groundwater depletion (7), waterlogging, and salinity. Aging canal irrigation infrastructure and loss of reservoir storage capacity due to sedimentation have made surface irrigation deliveries less reliable (8) and driven increased groundwater pumping (9). Whether agricultural production and environmental quality can be sustained for the large population of the IRB region remains a highly uncertain yet important question, and similar questions face many other developing countries.

Significance

Models for informing sustainability interventions in complex adaptive systems involving nature-society interactions are challenging to construct due to lack of detailed, quantitative data on the changing structure of system interactions. Here, we develop an approach combining qualitative descriptions of system components and interactions, with network representation for quantitative characterization of system structure. We demonstrate this approach with retrospective and prospective analyses related to food production in Pakistan's Indus River basin. Results identify the nodes and increasing number of pathways associated with sustained food production. Future scenarios point to production vulnerability due to conversion of arable land with implications on livelihoods for laborers and small-business owners and highlight the importance of coordinating rural and urban water and land-use policies.

This paper is part of a Special Feature on Modeling Dynamic Systems for Sustainable Development. The collection of all PNAS Special Features in the Sustainability Science portal is available here: https://www.pnas.org/sustainability-science.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2215682121/-/DCSupplemental.

Published April 22, 2024.

Here, we study the IRB to explore insights for a region that has an extensive history of optimization and integrated agro-economic modeling studies. The IRB served as an early case where methods of "systems analysis" were applied for development problems in the 1960s (10), and since then such efforts have continued to study prospects of water availability and agricultural production (7). Existing modeling approaches typically require extensive contemporaneous data and parameterizations for evaluating the implications of technical, investment, and policy decisions (11, 12). However, they have limited ability to account for major institutional and knowledge changes and disruptive events that occur over the longer multidecadal timescales that affect food production and sustainability. Several studies, based on integrated simulation models, have repeatedly noted the ambiguity and uncertainty in long-range quantitative projections for agricultural production (13) and water availability (14) in the IRB. Integrated models typically describe historical changes by changing parameters, including quantitative factors that reflect technological change, and by conducting sensitivity analysis. Long-term qualitative studies in other contexts have noted that system structure and evolution of pathways over time are important for sustainability. For example, Tellman et al., examining long-term vulnerability to water risk, found that decisions on when and how to adapt over a multicentury timescale in Mexico City had important feedback on risk management, and noted that "accumulation of deliberate decisions" creates the range of choices that are available in each period (15).

Network modeling offers unique opportunities for studying the "simultaneous effects of multiple social, environmental, and coupled processes, and change over time" (16), and it can provide an approach for assessing the changing institutions and knowledge in system modeling. Also referred to as graph modeling, network modeling involves a set of quantitative techniques related to analysis of components (nodes) and their connections (edges) (17). Prior studies have used networks to represent socioecological interactions to study the sustainability of coral reefs, fisheries (16), and forest wildlife conservation (18). In such studies, trophic interactions between fish species, social communication among human groups (or households), and harvesting interactions between humans and fish are modeled as networks. Recent work has used network methods to examine the sustainability of fisheries influenced by information-sharing networks (19), farmers' decision-making under drought risks (20), and subsistence food flows in indigenous communities (21). In a recent review of sustainability science, Clark and Harley observed that patterns of connectivity among components in a system matter for adaptive capacity (22), and noted that network approaches could advance the theoretically grounded progress needed for resolving how connections can be managed to promote adaptive capacity (23). Other reviews, however, have noted that network modeling remains challenging due to the substantial costs of collecting the necessary social and ecological data (24), and that applications have mostly centered on relatively small datasets or populations such as island communities (19), remote regions (21), and short time periods (a few years). Furthermore, selection of nodes and links (to define networks) in most studies has not followed a consistent framework related to sustainable development.

Here, we develop and test a mixed qualitative-quantitative approach to study how changes in long-term system structure relate to food production in the IRB region, and to identify vulnerabilities that may affect its future sustainability. Our approach links a qualitative systems-oriented sustainability framework with a network model. To provide theoretical grounding for network model construction, we use the Human-Technical-Environmental (HTE) systems framework (25), wherein we first identify H, T, and E components relevant for food production and consumption. Then, we qualitatively describe pair-wise interactions between them in a matrix representation, together with institutional (I) and knowledge (K) components that mediate those interactions. We convert the matrix into a binary, directed network, and conduct quantitative analysis of the network structure to investigate two questions: 1) How do quantitative metrics of network structure relate to observed

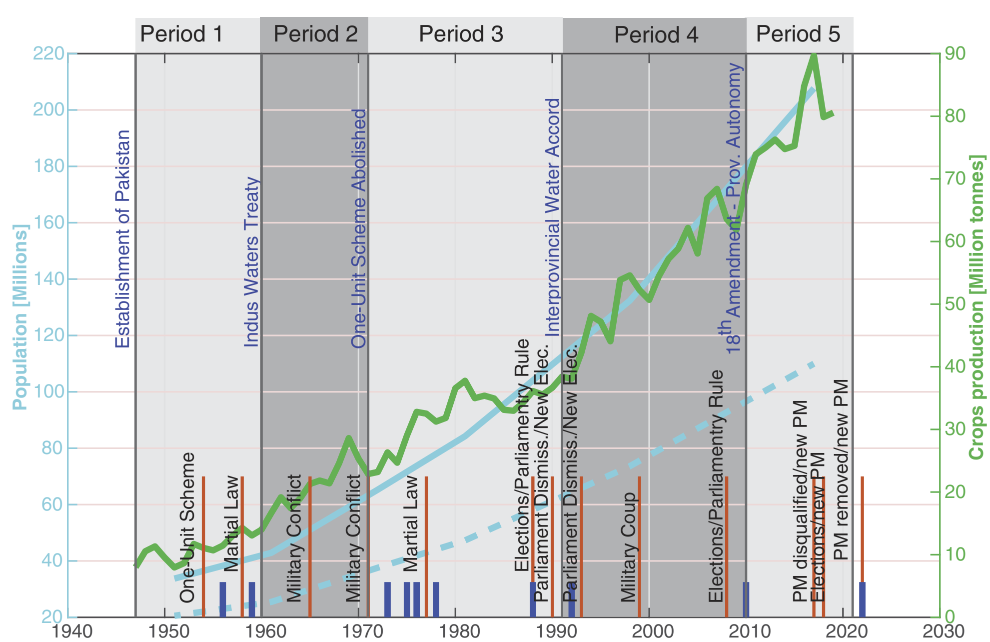

Fig. 1. Population, crop production, floods, institutional change, and political disruption events in Pakistan. The green line is crop production in Punjab. Solid and dashed cyan lines are population of Pakistan and Punjab respectively. Five periods: 1947 to 1959, 1960 to 1970, 1971 to 1990, 1991 to 2009, and 2010 to 2022, are used to study evolution of the food production and irrigation system. Each period begins with a major institutional change (shown in blue text). The short thick blue lines mark years of exceptionally high flood as defined by the Federal Flood Commission (4). Political events (in black text along red vertical lines) are military interventions, parliamentary dismissals, or unscheduled prime ministerial change and are considered as disruptions in this study. See *SI Appendix*, sections S1 and S2 for details.

sustainability-relevant outcomes over time? and 2) How can changes in these quantitative metrics resulting from potential interventions provide useful information about their systemic implications? We explore these questions for Punjab—the most populated and largest agricultural province in Pakistan—over 75 y (1947 to 2022), segmented into five periods marked by major institutional change (Fig. 1). To address our first question, we conduct a retrospective analysis of crop production since the mid-twentieth century, developing hypotheses about system characteristics that influence sustainability-relevant outcomes. To address our second question, we examine how two selected interventions affect networks and associated quantitative metrics.

Interactions in IRB Agriculture as Networks

We constructed five matrix representations of the IRB system in successive periods, using the HTE framework (*Methods*), and then transformed these matrices into networks (N_t where t refers to periods 1 to 5). The separate periods were demarcated based on the timing of dramatic institutional changes, either in overall governance (e.g., independence, war, martial law) and major land and water policy changes in the IRB (e.g., national land reforms, international water treaty, and major changes in national water policy) (see *Methods* and *SI Appendix* for further descriptions). We specified interactions among components in the matrices based on published literature (26, 27). A summary of the regional context and its history is provided in *SI Appendix*, section S2.

For each network, H, T, and E (material) components are represented as nodes. Interactions between pairs of H, T, and E components (described with text in the HTE matrix) are encoded as ones or zeros in a corresponding numeric matrix. This binary matrix is an adjacency matrix, A, that represents a directed network with the element in the ith row and jth column, $A_{ij} = 1$ if a link directed from node i to node j is present. In this way, the numeric matrix is used for computing structural and connectivity properties of the network. The corresponding textual descriptions of the interactions, and of I and K components associated with those interactions, are used to understand pathways within the system. For instance, one of the H nodes is "laborers and artisans", a T node is "land cultivation and harvesting equipment"; and a directed interaction from the H to the T node is "use and maintain [I40, K1]". The institutional component (I40) and knowledge component (K1) indicate that laborers and artisans "use and maintain" land cultivation and harvesting equipment based on their knowledge of cultivation techniques (K1) and rules of labor markets (I40).

All components in the model are numbered, and their descriptions and details of construction of the HTE matrices are provided in *SI Appendix*, sections S3 and S4. Fig. 2 illustrates the conceptual construction of the qualitative matrix and its associated directed network (*Top* row), and the full networks N_1 and N_5 (*Bottom* row), illustrating both the overall increase in links, and the addition of institutions and knowledge over time.

Results

We first evaluated our network representation by comparing the resulting pathways [i.e., connected sequences of links between pairs of nodes, see *Methods* (17)] with empirical data from qualitative system descriptions. We also used historical information to test how well quantitative metrics of network structure, specifically centrality, reflected the influence of past interventions. After this evaluation and testing, we then analyzed quantitative metrics of network structure, node centrality, and length of pathways between human and food components over time in the IRB system to elicit additional insights over the five periods (see *Methods* for calculation details). Finally, we analyzed two potential policy interventions: regulation of groundwater pumping; and phasing-out fossil fuels in the agricultural sector.

Evaluation and Testing of Pathways. In constructing the matrices, we defined pair-wise interactions between components based on published studies (10, 28–30) as well as census and official statistics (26, 27), without assumptions about the larger structure of complex interactions in the system. We assessed the reliability of this approach by examining whether the more complex pathways that include multiple, linked pair-wise interactions in the model corresponded with historical and empirical knowledge of the system relevant to food production and sustainability outcomes. For instance, during period 2 (1960 to 1970), the use of improved seed varieties (including semidwarf wheat and rice varieties developed in collaboration between Pakistan's national agricultural research system and the International Maize and Wheat Improvement Center in Mexico and the International Rice Research Institute in the Philippines respectively) substantially expanded in Punjab (28). This so-called green revolution increased production of major crops by 9 percent per year during 1966 to 1970 (28). Based on this history, we added a pair-wise interaction (in period 2) of laborers handling improved seeds on farms, and another interaction of improved seeds increasing yields of crops on irrigated lands for on-farm consumption. Inspection of resulting pathways (for period 2) show the logic of how laborers and artisans could support their food needs through use of improved seeds that increased yields (and therefore total production), and that in turn elevated the quantity of produce (through sharecropping) that the laborers could receive for their consumption. More details are provided in *SI Appendix*, Table S5.1.

Another example used for evaluation is in period 4 (1991 to 2009) when an Interprovincial Water Accord (IWA) for sharing waters of the Indus and its tributary rivers among provinces was adopted, and implemented by a new Indus River System Authority at the federal level (30). The IWA set up water apportionment rules and a process for seasonal volumetric allocations through semiannual discussions between federal and provincial officials, enabling water availability for agriculture. We modeled the IWA as an institutional component and included three pair-wise interactions in the system matrices for periods 4 and 5 to show its mediation of seasonal water allocations. The resulting pathways connecting "federal government officials" to canals were then examined, and the results (discussed in detail in *SI Appendix*, section S5 and Table S5.2) show pathways that appropriately align with the sequence of federal-provincial interactions in the distribution of Indus waters. Additional evaluation is described in *Methods*.

Evaluation and Testing of Centrality Measures. We analyzed networks for the five periods using two node centrality measures: degree and betweenness (17). The degree (integer number of links to or from a node, v), quantifies the number of connections to v. The betweenness for a node is a measure of how often v lies on the shortest pathways connecting any two nodes in the network (17). A node's degree provides a measure of its direct connectivity with other nodes in a network, while betweenness provides a measure of a node's location among pathways in a network.

These two measures together describe two structural properties of a network that have important implications for network function, and the literature on networks and sustainability highlights these two characteristics to be closely related to continuity of system function and resilience (31, 32). For instance, the flow of

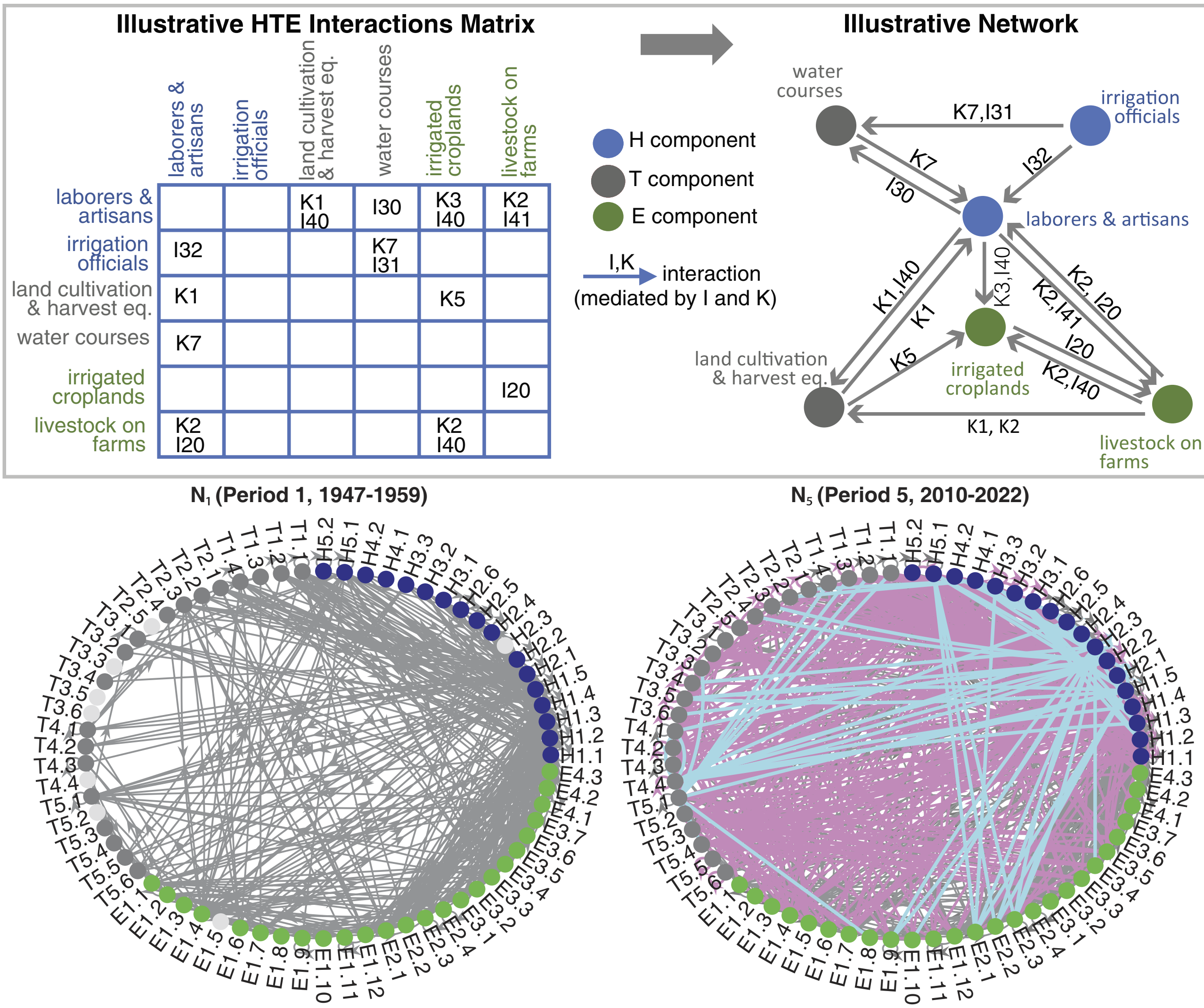

Fig. 2. Network representation of systems with interacting H, T, and E components. The Top box shows an illustrative part of an interactions matrix and its corresponding network with two H (blue), T (gray), and E (green) components (nodes) forming a system based on their interactions mediated by I and K components. The Bottom row shows networks N_1 (1947 to 1959) and N_5 (2010 to 2022), in a circular visual layout, representing the irrigation and food production system in the IRB of Punjab, Pakistan. Nodes not connected to any links in N_1 (Bottom Left) are shown as light gray dots. Links in N_5 (Bottom Right) that did not exist in N_1 are colored magenta and cyan in N_5 and show increased connectivity in the system over time. Magenta links are new links associated with institutions and knowledge components that existed in N_1, while cyan links are associated with new institutions and knowledge components absent in N_1 and present in N_5. See *SI Appendix*, Tables S3.1–S3.3 for key to component numbers.

information, energy, water, goods, and people is affected if nodes with high centrality are affected (17). In a social network, an actor (node) with high betweenness can have considerable influence within a network, and their removal from the network will maximally disrupt communications between other nodes because they lie on the largest number of paths (17). Regarding resilience, an important finding is that networks where most nodes have few links but some nodes are highly connected (i.e., large degree) are "surprisingly" tolerant against "random failures" (33) because most of the nodes can be removed without noticeable impact on network structure. However, these networks are vulnerable to targeted attack on highly connected nodes (33). These networks with highly connected nodes are thus simultaneously robust to failures of many random nodes but vulnerable to failures of some specific nodes of high degree.

To test whether centrality and betweenness are representing useful characteristics of the IRB system, we simulated a historical policy intervention, the One-Unit policy implemented in 1954 that abolished provinces in the region. We used the period 1 (1947 to 1959) interactions matrix to construct two test interaction matrices of before (1947 to 1954) and after the intervention (1955 to 1959). In the 1947 to 1954 matrix, provincial officials had interactions mediated by provincial institutions, and in the 1955 to 1959 matrix, all interactions with provincial officials were removed to simulate abolishment of provincial offices, and new interactions were added that were mediated by martial law regulations. Test results showed centrality measures are higher in the postintervention network for federal government officials, which correspond to the expansive powers of centralized government at the time. An additional component that gained centrality in this test was hydropower development, which dramatically expanded beginning in the 1950s. Network representations with only knowledge-mediated links and only institution-mediated links were also used to analyze components' centrality shifts. Test results showed that foreign finance and expertise providers were most affected in the K-only network, and water in aquifers gained most centrality in the I-only network post intervention. These results align with historical policies that were used postintervention for engaging foreign donors and experts in regional water and energy infrastructure development, and policies for groundwater pumping to address salinity and water logging challenges. *SI Appendix*, section S5.2 provides more details and a discussion of sensitivity of results.

Evolution of Component Centrality. The Top row in Fig. 3 shows degree (normalized by maximum value) and betweenness for all nodes in periods N_1 and N_5. While all nodes are plotted, we labeled the top dozen nodes by degree in these periods. "Large farm owners" have the highest degree and betweenness through all periods. While their position in the system remains dominant, their centrality relative to small and medium farms diminished. In later periods, additional nodes including federal government officials and "domestic consumers" increase in degree and betweenness. "Water in rivers" and "livestock on farms" are two prominent environmental nodes, and "value-adding industrial facilities" emerge as a prominent technological node in later periods in the system. More details are provided in *SI Appendix*, section S6.

The Bottom row in Fig. 3 shows node betweenness and degree across the five periods of the nodes that on average had the highest change (instability) in these two measures. A few nodes with the least change (most stable) are also shown for comparison. "Researchers and innovators" increased in both degree and betweenness over time. Foreign and domestic "loans and expertise providers" also gained in betweenness. Together, this may help explain part of the agricultural production gains evident in the system. "Village councils" experienced changes in betweenness across the periods, reflecting the centralization and decentralization of governance institutions in Pakistan (see *SI Appendix*, section S2 for details). "Hydropower machinery" shows gains in both betweenness and degree over time—highlighting salience of this technical component in the IRB system. This also points to a key vulnerability related to climate change, as hydropower systems are vulnerable due to uncertainties in future hydrological flows. More details are shown in *SI Appendix*, Figs. S6.3–S6.6.

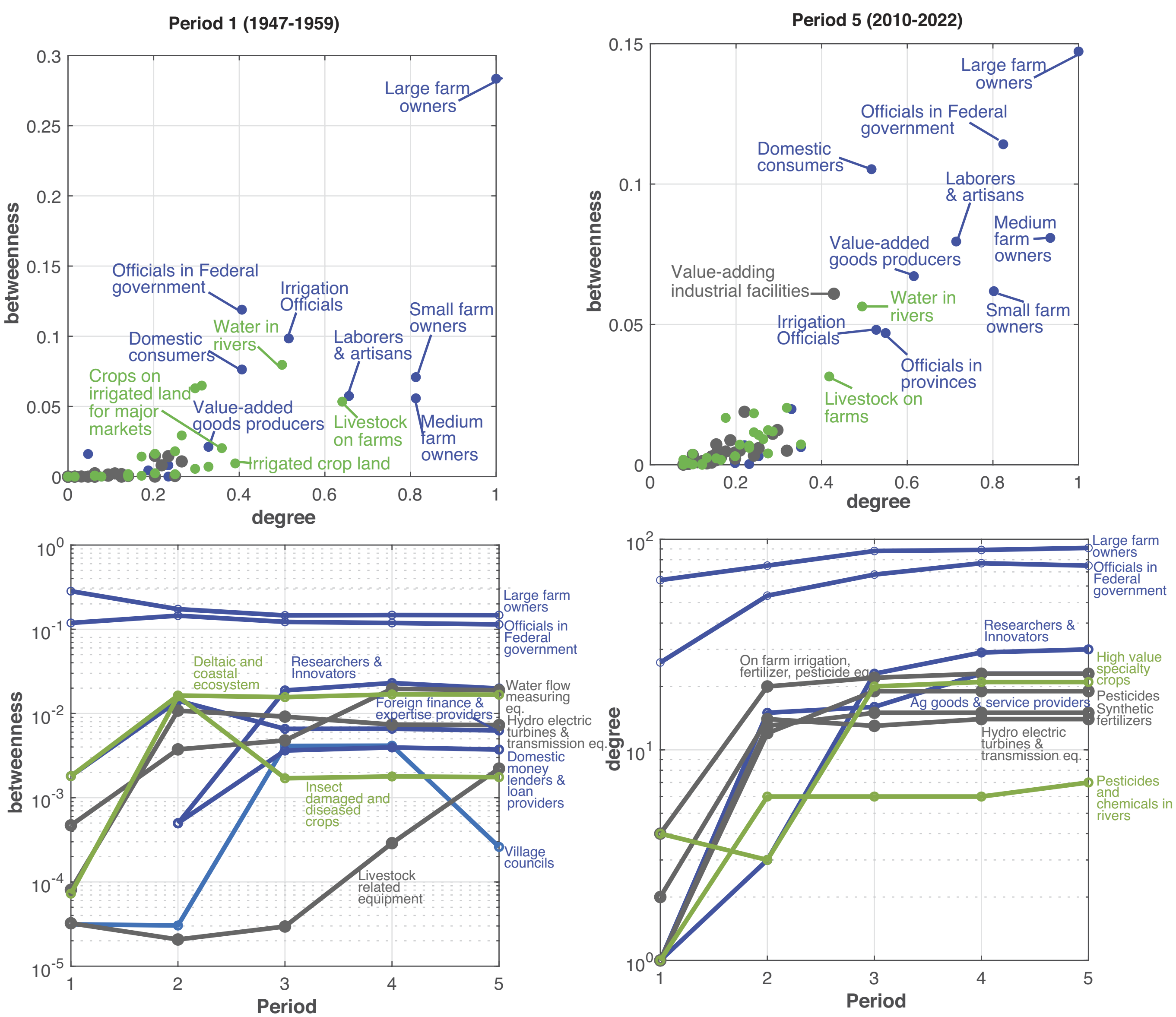

Fig. 3. (*Top* Row) Degree (integer number of links to or from a node) and betweenness (how often a node lies on the shortest pathways connecting any two nodes), shown for the first period and last periods for all nodes (components). Normalized values of degree are shown for visual clarity, and top dozen nodes by degree are labeled. (*Bottom* Row) Betweenness and degree of components is shown for each of the five periods. Only components with the highest change in betweenness or degree are shown. For comparison, two components, large farm owners and federal government officials are also shown that remain relatively stable in centrality within the system.

Our results thus show that the node with the highest centrality (both degree and betweenness), large farm owners, persists with the highest centrality despite natural and political disturbances across N_1-N_5, while additional nodes in the system gained centrality (both degree and betweenness). This corresponds to our understanding from qualitative studies that large farm owners have retained control over land ownership and production activities and continue to have a substantial degree of power and influence (29) sometimes characterized as "feudal" or "tribal" (10). However, increasing network connectivity of laborers and artisans and medium farm owners (Fig. 3) point toward multiple trajectories of food production in the IRB system. Land fragmentation has occurred in the region (see census data in *SI Appendix*, section S2.1), and our analysis complements this understanding by quantifying changes in node centrality over time. Results also show increased centrality of federal government officials, and reflect strong state vis-à-vis market forces. There is also increasing centrality of domestic consumers, along with a comparatively large increase in both betweenness and degree of researchers and innovators in the system.

In our main analysis, we also considered the influence of institutions and knowledge jointly when indicating their associations with interactions. To explore their relative importance in changes to the network, we conducted additional analysis to compare network representations with only knowledge-mediated links and those with only institution-mediated links. Farm owners and laborers (producers) have high betweenness and degree in both I-only and K-only networks. The federal government and irrigation officials (rule makers) have high centrality in the I-only network, and ecological and technical components have high centrality in K-only networks. Detailed results are discussed in *SI Appendix*, section S6 and Figs. S6.7–S6.10.

Interaction Pathways between Humans and Food Components. We examined the number and length of pathways connecting nodes representing key human components to nodes representing food components, as indicators of the system function of food production. The number of paths connecting a pair of nodes is related to a network's robustness: if some links fail, connectivity may be maintained due to multiplicity of paths between nodes (redundancy). Pathway length is a measure of the number of intermediaries connecting a pair of nodes, and short average path lengths in networks are associated with efficiency. The balance between efficiency and redundancy in the network structure has been noted as a principle of system robustness and resilience (32), and relates to sustainability (31).

In our model, some of the links (pair-wise interactions identified in the HTE matrix and used as inputs to the network model) connecting human nodes directly to food nodes and their associated institutions were maintained through all five periods (*SI Appendix*, Fig. S7.1). These reflect subsistence agricultural practices in which laborers and artisans, and small farm owners, directly consume food produced on farms, to partly meet their nutrition needs. Additional links maintained over the five periods include those in which consumers purchase crops and livestock produce from large and medium farm owners (see *SI Appendix*, section S7 for more discussion).

In the networks, we also determined longer pathways that connect human and food nodes and found that these increased in number and length over time (Fig. 4 and *SI Appendix*, Figs. S7.2–S7.6). This suggests that multiple alternative ways of food production and consumption developed that affect food security. For instance, as shown in *SI Appendix*, Fig. S7.3, pathways of length 3 between laborers and artisans and "crops for on-farm consumption" included interactions with technological nodes beginning in period 2; and pathways of length 4 included multiple H, T, and E nodes in all periods, indicating growth in the diversity of interacting nodes and pathways in the food system. On one hand, the longer pathways showed new connections and attendant robustness; but they also indicate that several components need to successfully interact along the pathway and thus suggest potential vulnerability (if any component or link were to fail).

The number of unique pathways (of length 3) changed between N_1 and N_5 from 10 to 12 connecting laborers and "crops on farms"; from 15 to 27 connecting large farm owners and "crops for markets"; and from 7 to 12 connecting domestic consumers and crops for markets. This suggests new interactions and potential for affecting production (and income) for producers and consumption (and nutrition) for consumers. Interestingly, these pathways have different associated I and K components than the pairwise links (*SI Appendix*, Figs. S7.3–S7.6). For instance, pairwise links between laborers and "crops on irrigated land for on-farm consumption" are associated with K1 (knowledge of cultivation techniques), and new pathways between these two nodes in period 5 include K11 (knowledge of human health and nutrition). This component (K11) was not associated with any pathway between these nodes in period 1 (*SI Appendix*, Table S7.3*B*), which indicates addition of knowledge in the system.

Future Scenarios of Water and Energy Policies and Implications. To explore changes in system structure associated with potential future actions to promote sustainability in Punjab, we considered two illustrative future interventions and their implications for the food system: a groundwater policy and an energy policy.

The Pakistan National Water Policy adopted in 2018 lists "regulation of groundwater withdrawals for curbing overabstraction and promoting aquifer recharge" as one of its primary objectives (34). Concerns about the sustainability of groundwater, given extensive pumping (35), have motivated several studies on groundwater abstraction regulation (36).

To simulate a scenario of future groundwater pumping regulation, using our model, we removed links connected to the node "groundwater extraction machinery" in the system network in period 5 (N_5) and produced a new network, N_5^{water}. This total cessation of pumping was used as an illustrative bounding scenario to assess systemic implications. In the extreme case, N_5^{water} can also simulate the depletion and collapse of groundwater irrigation. We then analyzed how pathways changed between human and food nodes as an indicator of sustainability-relevant outcomes (Fig. 5). We also determined which nodes had highest centrality shifts between N_5 and N_5^{water}, and examined pathways associated with those nodes to understand implications. Additionally, we analyzed centrality shifts in K-only $\left(N_5^K \ and \ N_5^{K-water}\right)$ and institution-only $\left(N_5^I \ and \ N_5^{I-water}\right)$ networks for identifying salient components for policies.

A primary impact of the policy scenario was that pathways changed that connect groundwater extraction machinery to "on-farm irrigation equipment", impacting crop yields. This result is consistent with past studies (37), and is discussed in detail in *SI Appendix*, section S9.

The centrality shifts in the K and institution networks (details in *SI Appendix*, Figs. S9.6 and S9.7) showed the relevance of knowledge for irrigation officials to effectively use modern communications equipment for surface irrigation, and K for effective use of on-farm equipment. Additionally, policy provisions for groundwater pumping for controlling salinity and water logging will be needed to manage salts and water in root zones.

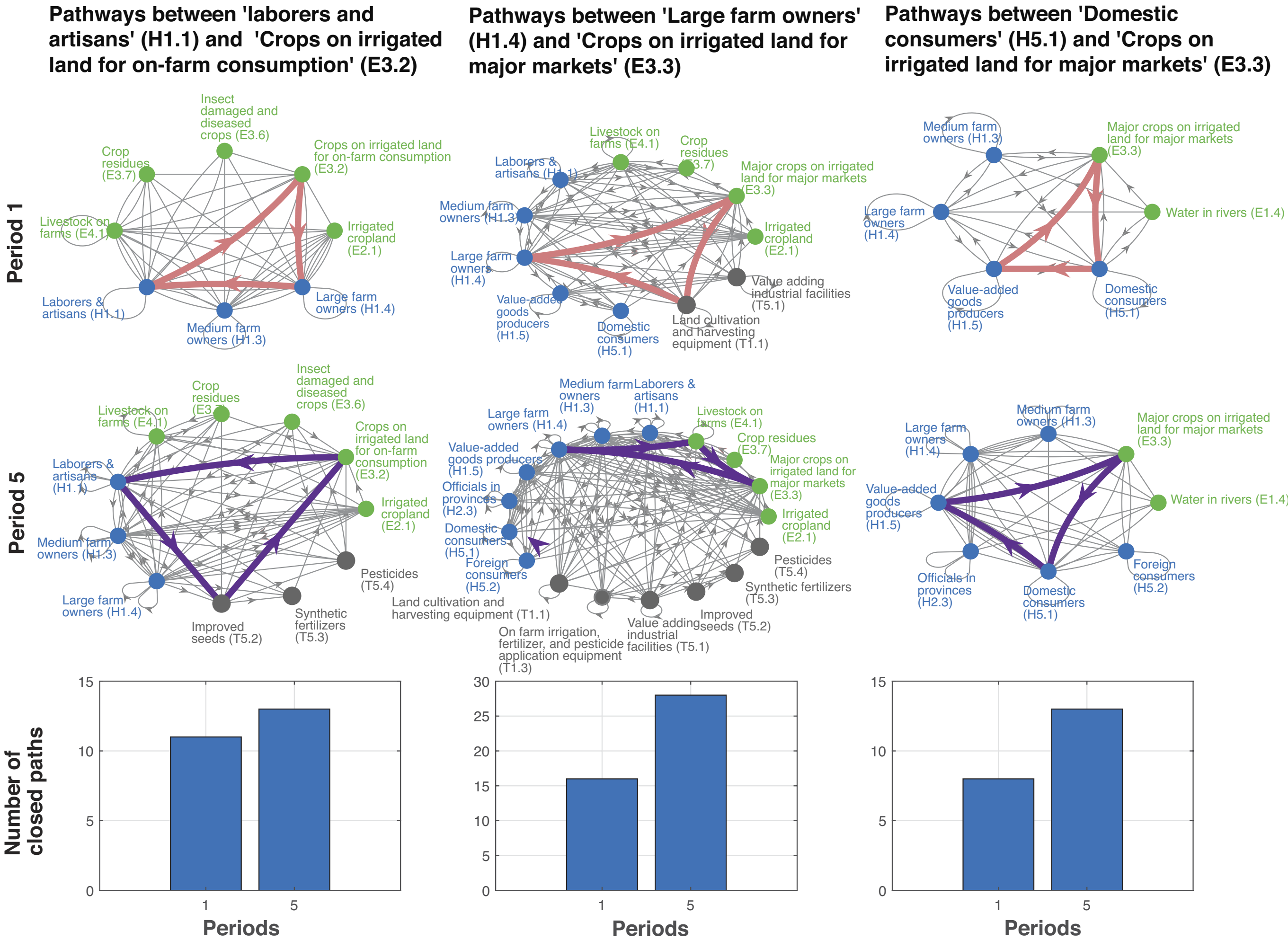

Fig. 4. Pathways of length 3 in N_1 (Top row) and N_5 (*Middle* row) between human and food-related environmental components. For visual clarity, subnetworks (instead of full networks) are shown. Highlighted (red) pathways in the Top row show a pathway linking a human and food component in period 1 (1947 to 1959). Highlighted (purple) pathways in the *Middle* row show pathways in period 5 (2010 to 2022) that did not exist in period 1. The Bottom row shows the number of closed paths between those components for periods 1 and 5. See *SI Appendix*, Tables S3.1–S3.3 for key to component numbers.

Our model also yielded further insights of pathways that have not been considered, to our knowledge, in previous analyses of groundwater regulation. Preintervention (in N_5) there were pathways connecting groundwater extraction machinery to laborers in farms and in industrial facilities (of parts manufacture and sale), which were not present postintervention (in N_5^{water}), highlighting potential implications for employment income of laborers and artisans due to effects on farm irrigation as well as industry.

Results also indicated alterations of pathways associated with land use. A pathway involving groundwater extraction machinery and internal combustion (IC) engines indicated that groundwater pumping enables irrigation of croplands, and some of those croplands are being converted for housing developments (*SI Appendix*, section S9). These pathways suggest that pumping curtailment may affect productivity of land and in turn may accelerate turnover of arable (and arid) lands to housing development. In the absence of groundwater regulation, land conversions associated with groundwater depletion could be extensive and unguided. This would create an important structural shift in the system, as agricultural production on arable land underpins food production, particularly for laborers and artisans who do not own but work on croplands in the region (*SI Appendix*, section S9). While sale and transfer of land may bring benefits to landowners, laborers and artisans would be adversely affected through loss of work on farms sold for housing, along with loss of "in kind" payments in farm produce that they formerly received in exchange for labor (see *SI Appendix*, section S8 for details on in kind income). Groundwater regulation policies in the region should thus consider land use, food production, and livelihoods, as well as water management.

To explore how future energy policy could affect the IRB system, we considered the phasing-out of fossil fuel use in agricultural production. Globally, electrically powered agricultural machines are emerging for transitioning out IC engines (38). Use of such machinery can save fuel costs for farmers, as fossil fuel prices are high and volatile in the IRB region, and it can also reduce emission of green-house gases. A fossil fuel phase-out was simulated by removing all links connecting with "Fossil fuel" node in N_5 to obtain a new network, N_5^{energy}.

The influence of the policy on sustainability-relevant outcomes is illustrated by changes in pathways and centrality metrics that influence income for farm owners and as well as hydropower generation. The pathways that were affected showed that farm owners sell crops to industrial facilities (partly powered by fossil fuel) that manufacture "value-added goods" (such as processed foods and textiles). This pathway is affected and can impact earnings for farmers if industrial facilities are affected (see *SI Appendix*, section S10 for details). A comparison of centrality shifts in nodes

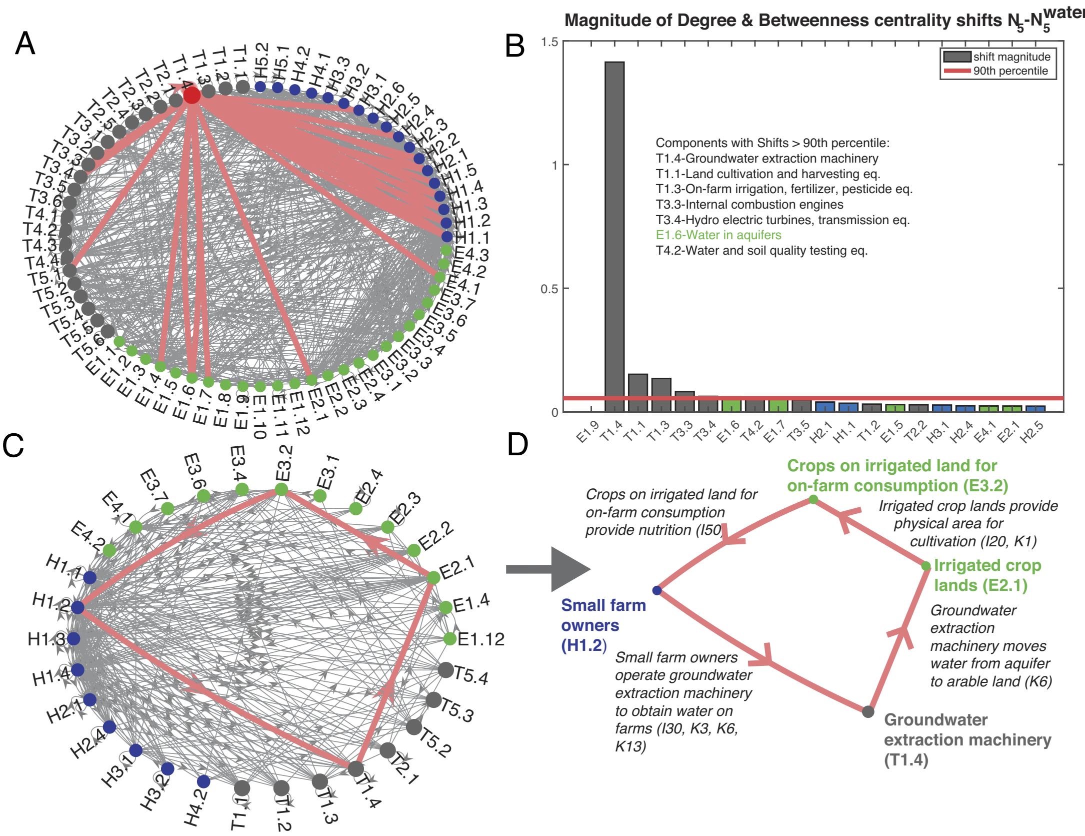

Fig. 5. Links connecting to "Groundwater extraction machinery" (T1.4) are displayed in red in the network of period 5 (N_5) (panel *A*). The node for T1.4 is enlarged and colored red for visual clarity. The red links are removed when simulating cessation of groundwater pumping scenario. The components with the highest aggregate centrality shift are shown in descending order in panel *B*). These include machinery related to farm operations and water in aquifers. Details of degree and betweenness change are in *SI Appendix*, section S9.4. Panel (*C*) shows a subnetwork of pathways of length 4 in N_5 consisting of small farm owners (H1.2) and "crops on irrigated land for on-farm consumption" (E3.2). The highlighted (red) pathway shows a particular pathway in N_5 that would be disrupted if Groundwater extraction machinery (T1.4) is removed from the network. The text associated with each link of the pathway is shown (in black font) in panel *D*. See *SI Appendix*, Tables S3.1–S3.5 for key to component numbers.

(in N_5 and N_5^{energy}) showed that "IC Engines" and Value-adding industrial facilities (that use fossil fuel) lost the most centrality as expected (*SI Appendix*, Fig. S10.2). The node, "Water in reservoirs" also had a high centrality shift, pointing to salience of stored water for hydropower if fossil fuels were phased out in this region.

More surprising results from the energy policy scenario included changes involving "Ag goods and service providers", and Land cultivation and harvesting equipment as nodes with high centrality shift (*SI Appendix*, Fig. S10.2). Our examination of pathways showed that agricultural goods and services providers are impacted by the simulated policy of fossil fuel phase-out since these businesses are dealing with equipment and products that run on fossil fuel. This policy affects their supply chains, their sales of parts and maintenance services, and their overall business viability. The existence of this pathway draws attention to the need for assessing and potentially mitigating unintended consequences of disrupting small local goods and services providers in the agricultural sector. Similarly, machinery for land cultivation represents sunk costs for farmers. Under fossil fuel phase-outs, that machinery would need to be either retrofitted (to operate on electrical power) or replaced. Centrality shifts in K-only $\left(N_5^K \text{ and } N_5^{K-energy}\right)$ and I-only $\left(N_5^I \text{ and } N_5^{I-energy}\right)$ networks showed that training for laborers will be needed for operating and maintaining electrically powered equipment (*SI Appendix*, Fig. S10.6 and S10.7).

Discussion

The network modeling approach presented here enables analyses of both historical evolution and future interventions for sustainability. It can be used to illustrate changes over time in system structure, including consideration of new and altered institutions and knowledge, without relying on large, high-resolution datasets. The ultimate goal in studying networks is to better understand the changing structure and behavior of the system that the networks represent, and an important step is to make the connection from network structure to function through interactions that occur within and between periods (17). Our use of concepts from network theory, such as node centrality and path length, facilitates the study of which connections matter for sustainability. Our results identify specific pathways, as well as their number and length, that serve as mechanisms affecting the robustness of food production over the five periods studied. Future scenarios modify pathways and connectivity in ways that may affect food production vulnerability, such as loss of arable land and effects on small businesses and laborers.

Relevant to our first question on how quantitative metrics of network structure relate to sustainability-relevant outcomes, we posited that the overall number of pathways may be considered as measures of the adaptive capacity of the system to sustain important functions such as food security even in the midst of disruptive events. In the IRB system, we showed links connecting humans to food nodes have persisted despite natural disasters and political turmoil

(10), and they have been mediated by informal institutions and knowledge (*SI Appendix*, Fig. S7.1). Importantly, we showed how these links were augmented by additional longer pathways over time that contributed to growth in food production. This provides a more complex representation than discussions in the literature on households either being stuck in declining yields in traditional livelihoods (poverty trap), or abandoning an activity (fishing) altogether (39). In the case of farm households in Punjab, an expanding combination of livelihood pathways that include different members of the household engaged in farming, livestock rearing, and working in factories and urban areas (domestic and foreign), collectively produce and purchase food for household members and markets. Overall, the IRB food production system experienced oscillating centralization and decentralization in governance (e.g., see centrality of Village Councils in Fig. 3), with some persistent as well as emerging actors. No single development narrative can account for this complicated record of system evolution that becomes vivid through our analysis. Perhaps the most significant result in systemic terms is the increasing plurality of paths connecting humans and food nodes that shaped production over time, and to date averted famine (though the level of nutrition remains a challenge).

Our case provides evidence that the degree and betweenness metrics are associated with system robustness and vulnerability, and it provides insights into how these can influence sustainability-relevant functions. We suggest that nodes with high betweenness and high degree can be considered as potential leverage points in a system. Leverage points are defined as places within a system wherein a small change "can lead to large changes" in the overall system (40). In the case of the IRB, a structure containing a few nodes with high degree and increasing pathways may partly explain why food production does not collapse, since natural and political disturbances to the system did not lead to the "failure" of the highly connected nodes including large and middle farm owners. Due to the high degree of large farm owners, however, we suggest that the connectivity structure was also vulnerable in early periods (1 and 2) following independence, in that a collapse of this highly connected node would have affected food production. Several unsuccessful attempts to improve rural socioeconomic conditions during the examined periods centered on land reform policies that, if fully enforced, would have displaced large farm owners (28), and prominent impacts (some desired and possibly some undesired) on regional food production could have occurred. Instead, the system had a gradual decrease in the proportion of large farms and increase in proportion -- and connectedness -- of smaller farms in ways that contributed to sustained food production. Additionally, the increase in degree and betweenness of researchers and innovators in the system may partly explain the sustained increase in food production.

The persistence of nodes with high degree and betweenness over time, and their association with the maintenance of important network functions, also suggests insights related to their power and influence. Highly central human nodes (or actors) can acquire (and exercise) disproportionate control, creating biases in governance. In network terms, highly central human components offer the possibility of efficiency in interactions, decision-making, innovation adoption, or information flows. At the same time, such structures can lead to "unfair" and "undemocratic" governance with resultant vulnerability by virtue of the influential position of a few components (31), and historical analyses of the IRB have illustrated specific cases (10). While our analysis documented the persistent centrality of some actors, it shed light on the increased connectivity and pathways of others in the evolution and robustness of the IRB food production system.

These results also point to possibilities for the future. Domestic consumers achieve relatively high centrality from period 4 onward. With rising costs of food and value-added goods, the interactions of this node in pathways for purchasing goods may or may not continue, which affects this system of interdependent production and consumption. Government and military actors have had increasing influence on land and water resources. Further research could use the network structure to assess important trade-offs and risks associated with these changes in actor power relations over time.

Relevant to our second question, on whether changes in these quantitative metrics resulting from potential interventions provide useful information on their systemic implications, we showed that examination of pathways and network metrics resulting from an intervention illuminates connections and feedbacks that were not identified using previous approaches. For instance, pathways discussed in *SI Appendix*, section S9 highlighted conversion of arable land as an effect of groundwater regulation policy, and *SI Appendix*, Table S10.4 highlighted potential impacts on small-business owners from a fossil fuels policy.

Overall, the key finding of persistent centrality of producer nodes is robust to several choices made in the model construction process. Our focus on pathways related to components undergoing relative centrality shift at the 90th percentile or above in policy interventions means that the main results are relatively insensitive to single interactions that are specified differently. With respect to the selection of model components, however, a higher level of aggregation (for instance where farm owners and laborers are not separately represented) would make some results coarse such that differential understanding of different producers' vulnerabilities would not be distilled. Further applications of our method by different experts in future work would help to further assess the limitations of this mixed qualitative-quantitative approach.

Building on insights from our results, our method could be applied in the analysis of policy design alternatives. Policy interventions that affect the number and length of pathways, for example, could be examined as alternative adaptive strategies for complex river basins like the Indus. Furthermore, components that undergo high centrality shifts in knowledge and institution networks (as discussed in *SI Appendix*, sections S5, S9, and S10) can also point to the need for policy design for addressing specific knowledge needs and institutional provisions. To build further understanding, it will be necessary to consider how structural properties of networks relate to sustainability outcomes, and how institutional context influences network evolution (41, 42). While our approach does not allow for causal inference, it can be used to develop counterfactuals (an essential part of causal analysis) and can help in formulating and evaluating hypotheses about the manifold relationships that create patterns of dependencies and risks, mediated by knowledge and institutions.

While we have developed and tested a method that addresses institutional and knowledge components, and their interactions in nature-society systems, important questions remain for future sustainability modeling, both in the IRB and beyond. We limited our analysis here to metrics associated with qualitative interactions to establish the utility of this approach for sustainability-relevant outcomes. Further analysis could examine approaches to quantitatively characterize pathways (43) and explore advanced statistical network methods such as exponential random graphs to study temporal evolution.

Degradation of the Indus riverine ecosystem and the delta (*SI Appendix*, section S11), along with aging technical infrastructure, also shape the challenge of future food security in the region. The magnitude of recent intense hydroclimatic events and flood disasters in 2010 (44) and 2022 are testing the resilience of food production. Previous developments in the region expanded the centralized canal irrigation system with a few large storage dams, but new developments may consider distributed systems that require lower costs of maintenance and are governed by locally suited rules. New approaches for governance are being proposed (45), and new technologies for efficient and "smart irrigation" are being developed for the IRB (46). These developments suggest that systemic changes and new pathways will continue to characterize the region with important implications for sustainability.

The long arc of human history in the IRB has been punctuated by multiple episodes of natural and human-induced disasters. But the past century has seen expanding food production roughly keeping pace with population growth. This study traces the structural changes and internal paths that have led to that outward (observed) trajectory and provides an approach to examine implications for future sustainability in food production. The present and future challenge is to ensure that necessary network reconfigurations, including addition of new links (interactions) and nodes (components), and removal of unnecessary (or adverse) interactions and components occur, such that manifold new paths open for restoring and replenishing the productive potential of the region for future generations.

Methods

We used the HTE systems framework, developed to advance systems-focused research on sustainability issues for researchers with different disciplinary backgrounds (25, 47). The HTE framework uses a matrix representation of system components and their interactions, which enables the examination of interventions that target components and/or their interactions. The HTE framework includes three categories of material components—H, T, and E. Two nonmaterial categories, institutions, and knowledge, provide the mediating context within which the material components interact. Institutions are defined as sets of rules, norms, and/or policies (48, 49). Knowledge includes research, data, and decision support on system components and interactions.

We applied the first two steps of the HTE framework of identifying system components and their attributes and then describing interactions among those system components (25). The components (and their attributes), and interactions were chosen for their relevance to irrigation and food production in the region. We then converted the qualitative (textual) description in the matrix into a binary network representation, wherein the H, T, and E (material) components are nodes, and their interactions are links with associated I and /or K components. This results in a binary-directed, multiplex network representing the logical structure of interactions connecting system components. We defined interactions only for pairs of H, T, and E components (nodes), but the resulting network reveals how nodes form chains of interactions—i.e., interaction pathways—producing direct as well as indirect connections within the system. We identified pathways using a computational algorithm that determines all possible pathways associated with the networks. We then examined the textual information (of each link) to review the resulting paths. Thus, detailed quantitative data to describe each interaction is not required (although it can be used if available).

We modeled five periods spanning 1947 to 2022 of the irrigation and food production system in the Indus basin focusing on the Punjab province of Pakistan. Each period begins with a major institutional change: Period 1 (1947 to 1959) begins at Pakistan's independence. Period 2 begins with the signing and adoption of the Indus Waters Treaty (1960 to 1970). Period 3 (1971 to 1990) begins at the end of the "One Unit scheme" of governance and the independence of East Pakistan that became Bangladesh. Period 4 (1991 to 2009) begins with the adoption of the IWA. Period 5 (2010 to 2022) starts at the passage of the 18th Amendment to the Constitution, which recognized provinces as having jurisdiction over their natural resources. *SI Appendix*, section S2 provides a more detailed narrative on this institutional context and history. Institutions likely "change the trajectory of network self-organization processes" (41), therefore, while we do not interrogate causal effects of policy enactments, we use institutional changes as a basis to segment time periods for constructing and analyzing the evolving network structure.

System Description: Components. Following the HTE framework, we modeled five types of components: H, T, E, I, and K. We used a "medium level of aggregation" as discussed in ref. (24). From a resilience perspective, it has been noted that "it is necessary" to include "heterogeneity more explicitly" (31). Here, a heterogeneous network consists of 18 H components, 25 T components, and 26 E components (see *SI Appendix*, section S3 and Tables S3.1–S3.5 for details). We included agricultural components, e.g., crops and livestock, in the environmental category.

System Description: Interactions. We constructed a separate 69 × 69 matrix for each of the five periods to contain component interactions. We entered key interactions (if present) for each component pair in the system as text in a matrix. We chose interactions based on their relevance for affecting component attributes, and based on published literature (28–30), historical summaries (10), and publicly available data (26, 27).

Model Construction Process. The list of all components (H, T, E, I, and K) was first constructed in full by one expert, and then reviewed by the second. Through this expert-based cyclical process, the model representation was iteratively revised such that the process led to a final list of components deemed sufficient for exploring questions related to the irrigation and food production system (shown in *SI Appendix*, section S3). Once the components were finalized, the interactions matrix was fully constructed by the first expert, and then it was evaluated by the second expert, critiqued, and revised. *SI Appendix*, section S5 provides further details.

Network Formulation. We defined a network [called graph in mathematical graph theory (17)], N_t, for period t, as a pair: $N_t = (V_t, E_t)$. Here, V_t is a set of nodes [also referred to as vertices (17)] where each node corresponds to an H, T, or E component defined for the system in time t. E_t is a set of directed links (also referred to as edges) that are ordered pairs indicating source and target nodes. We wrote code [MATLAB release 2022 (50)] to convert the interactions matrix into a binary, directed, multigraph. Each link represents one interaction described in the interactions matrix for period *t*. A pair of H, T, and E components with multiple interactions in the matrix are thus represented as a pair of nodes with multiple links (edges) between them in the network. Each link in the network also has associated I and/or K components. See *SI Appendix*, section S4 for details.

Evaluation and Testing. Model testing was conducted qualitatively by sequential model production and then review and validation by two experts. This was done for components and then interactions. We performed two or more such iterations for each period. We analyzed pathways between selected nodes and evaluated their plausibility and logic against actual information about the system. Model robustness was considered by assessing implications of different level of component aggregation as well as choices of interactions on component centrality results. See *SI Appendix*, section S5 for details on this qualitative and quantitative testing. We also conducted tests for selected past interventions, and details are described above and in *SI Appendix*, section S5.2.

Network Centrality Measures. We used network functions in MATLAB (50) to compute centrality measures of degree and betweenness and to determine pathways between nodes.

The degree and betweenness are "comprehensive" (31) characteristics of a network, and "represent some of the very fundamental structural properties of importance in any kind of network and have been used to classify vulnerabilities of networks" (31). We defined the degree of a node v, $C_D(v)$, to be the sum of in-degree, k_v^{in} (the sum of links pointing to node v) and out-degree, k_v^{out} (sum of links pointing from node v):

$$C_D(v) = k_v^{in} + k_v^{out}.$$

The in-degree and out-degree for a node i is defined as (17):

$$k_i^{in} = \sum_{i=1}^{n} A_{ij},$$

and

$$k_i^{out} = \sum_{j=1}^{n} A_{ij}.$$

Betweenness of a node v was defined as (17):

$$g_v = \sum_{i \neq v \neq j} \frac{\sigma_{ij}(v)}{\sigma_{ij}},$$

where σ_{ij} is the total number of shortest pathways connecting node i to node j, and $\sigma_{ij}(v)$ is the number of pathways that connect through v (and v is not an end node). We normalize the betweenness by dividing g_v with the product $(n-1)(n-2)$, which is the number of pairs of vertices not including v in a directed network with n number of nodes.

To determine which nodes experience most prominent change (when comparing two networks that represent the system in different times), a set of measures were defined to quantitatively determine shifts in node centrality. Centrality change of nodes between two networks, N_t and N_{t+1}, was assessed by computing shift in degree and shift in betweenness of each node.

Betweenness shift was defined as.

$$\phi_v(t, t+1) = \frac{g_v(t+1) - g_v(t)}{g_v(t+1) + g_v(t)}.$$

The value for $\phi_v(t, t+1)$ varies between −1 and 1 and is a relative measure of change in betweenness of a node in periods t and $t+1$.

Degree shift was defined as.

$$\kappa_D(t, t+1) = \frac{C_D(v)\left[t+1\right] - C_D(v)[t]}{C_D(v)\left[t+1\right] + C_D(v)[t]}.$$

The value for $\kappa_D(t, t+1)$ varies between −1 and 1 and is a relative measure of change in degree of a node in periods t and $t+1$.

Aggregate centrality shift was defined as the 2-norm of betweenness shift and degree shift:

$$\Delta_v(t, t+1) = \sqrt{\phi_v(t, t+1)^2 + \kappa_D(t, t+1)^2}.$$

Network Pathways. We defined a pathway as a sequence of nodes such that every consecutive pair of nodes in the sequence is connected by a link pointing in a consistent direction (17). We showed pathways (in *Results*) as a sequence of nodes and links (since multiple links can exist between a pair of nodes).

Pathway lengths were defined as the number of links connecting a pair of nodes. Closed paths [also referred to as "cycles" (17)] are pathways that start and end on the same node.

Data, Materials, and Software Availability. Software code data have been deposited in Zenodo (51).

ACKNOWLEDGMENTS. A.S. was supported in part by funding from the Environmental Solutions Initiative at the Massachusetts Institute of Technology. N.E.S acknowledges support from the U.S. NSF (#1924148) for development and testing of the HTE Framework. We thank anonymous peer reviewers for helpful comments that have improved this paper.

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1. H. C. J. Godfray *et al.*, Food security: The challenge of feeding 9 billion people. *Science* **327**, 812–818 (2010).
2. P. Ehrlich, A. Ehrlich, G. Daily, Food security, population and environment. *Popul. Dev. Rev.* **19**, 1–32 (1993).
3. R. Wright, *The Ancient Indus: Urbanism, Economy, and Society* (Cambridge University Press, 2010).
4. Federal Flood Commission, Flood classification of major rivers. https://ffc.gov.pk/flood-classification-of-major-rivers/. Accessed 7 April 2024.
5. N. Bhattacharya, *The Great Agrarian Conquest: The Colonial Reshaping of a Rural World* (Permanent Black, 2018).
6. C. Singh, *Region and Empire: Panjab in the Seventeenth Century* (Oxford University Press, 1991).
7. W. J. Young *et al.*, "Pakistan: Getting more water—World Bank report" (Rep. No. 133964, World Bank, Washington DC, 2019).
8. J. L. Wescoat, A. Siddiqi, A. Muhammad, Socio-hydrology of channel flows in complex river basins: Rivers, canals, and distributaries in Punjab, Pakistan. *Water Resour. Res.* **54**, 464–479 (2018).
9. D. Mekonnen, A. Siddiqi, C. Ringler, Drivers of groundwater use and technical efficiency of groundwater, canal water, and conjunctive use in Pakistan's Indus Basin Irrigation System. *Int. J. Water Resour. Dev.* **32**, 459–476 (2016).
10. D. Gilmartin, *Blood and Water: The Indus River Basin in Modern History* (University of California Press, 2015).
11. W. Yu *et al.*, *The Indus Basin of Pakistan: The Impacts of Climate Risks on Water and Agriculture* (Directions World Bank Publications, 2013).
12. Y. C. E. Yang, C. Ringler, C. Brown, A. H. Mondal, Modeling the Agricultural Water–Energy–Food Nexus in the Indus River Basin, Pakistan. *J. Water Resour. Plan. Manag.* **142**, 1–12 (2016).
13. B. Droppers, I. Supit, R. Leemans, M. T. H. van Vliet, F. Ludwig, Limits to management adaptation for the Indus' irrigated agriculture. *Agric. For. Meteorol.* **321**, 108971 (2022).
14. M. Kirby, M. ud D. Ahmad, Can Pakistan achieve sustainable water security? Climate change, population growth and development impacts to 2100. *Sustain. Sci.* **17**, 2049–2062 (2022).
15. B. Tellman *et al.*, Adaptive pathways and coupled infrastructure: Seven centuries of adaptation to water risk and the production of vulnerability in Mexico city. *Ecol. Soc.* **23**, 1 (2018).
16. D. Salgueiro-Otero, M. L. Barnes, E. Ojea, Climate adaptation pathways and the role of social-ecological networks in small-scale fisheries. *Sci. Rep.* **12**, 1–13 (2022).
17. M. Newman, *Networks: An Introduction* (Oxford University Press, 2010).
18. C. L. Morgans, A. M. Guerrero, M. Ancrenaz, E. Meijaard, K. A. Wilson, Not more, but strategic collaboration needed to conserve Borneo's orangutan. *Glob. Ecol. Conserv.* **11**, 236–246 (2017).
19. M. L. Barnes, J. Lynham, K. Kalberg, P. Leung, Social networks and environmental outcomes. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 6466–6471 (2016).
20. R. van Duinen, T. Filatova, W. Jager, A. van der Veen, Going beyond perfect rationality: Drought risk, economic choices and the influence of social networks. *Ann. Reg. Sci.* **57**, 335–369 (2016).
21. J. A. Baggio *et al.*, Multiplex social ecological network analysis reveals how social changes affect community robustness more than resource depletion. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 13708–13713 (2016).
22. W. C. Clark, A. G. Harley, Sustainability science: Toward a synthesis. *Annu. Rev. Environ. Resour.* **45**, 331–386 (2020).
23. J. S. Sayles *et al.*, Social-ecological network analysis for sustainability sciences: A systematic review and innovative research agenda for the future. *Environ. Res. Lett.* **14**, 093003 (2019).
24. Bodin *et al.*, Improving network approaches to the study of complex social–ecological interdependencies. *Nat. Sustain.* **2**, 551–559 (2019).
25. H. Selin, N. E. Selin, The human–technical–environmental systems framework for sustainability analysis. *Sustain. Sci.* **18**, 791–808 (2022).
26. Bureau of Statistics—Government of Punjab, Punjab development statistics 2021. https://bos.punjab.gov.pk/system/files/PDS2021.pdf. Accessed 7 April 2024.
27. Government of Pakistan, Pakistan Bureau of Statistics, "Social & household integrated economic survey (HIES) 2018-19" (Government of Pakistan, Islamabad, 2020). https://www.pbs.gov.pk/publication/household-integrated-economic-survey-hies-2018-19.
28. D. J. Spielman, S. J. Malik, P. Dorosh, N. Ahmad, "Food, Agriculture, and Rural Development in Pakistan" in *Agriculture and the Rural Economy in Pakistan*, (University of Pennsylvania Press, 2017), pp. 1–40.
29. M. H. Khan, The structural adjustment process and agricultural change in Pakistan in the 1980s and 1990s. *Pak. Dev. Rev.* **33**, 533–591 (1994).
30. A. A. Anwar, M. T. Bhatti, Pakistan's water apportionment accord of 1991: 25 years and beyond. *J. Water Resour. Plan. Manag.* **144**, 05017015 (2018).
31. M. A. Janssen *et al.*, Toward a network perspective of the study of resilience in social-ecological systems. *Ecol. Soc.* **11**, 15 (2006).
32. B. J. M. de Vries, *Sustainability Science* (Cambridge University Press, 2013).
33. R. Albert, H. Jeong, A.-L. Barabasi, Error and attack tolerance of complex networks. *Nature* **406**, 378–382 (2000).
34. Ministry of Water Resources—Pakistan, "National water policy" (2018). https://mowr.gov.pk/SiteImage/Policy/National-Water-Policy.pdf.
35. A. Siddiqi, J. L. Wescoat, Energy use in large-scale irrigated agriculture in the Punjab province of Pakistan. *Water Int.* **38**, 571–586 (2013).
36. H. F. Khan *et al.*, Guiding groundwater policy in the Indus Basin of Pakistan using a physically based groundwater model. *J. Water Resour. Plan. Manag.* **143**, 05016014 (2017).
37. L. Lytton, A. Akhtar, B. Garthwaite, J. F. Punthakey, B. Saeed, *Groundwater in Pakistan's Indus Basin: Present and Future Prospects* (World Bank, 2021).
38. S. Gorjian *et al.*, The advent of modern solar-powered electric agricultural machinery: A solution for sustainable farm operations. *J. Clean. Prod.* **292**, 126030 (2021).
39. J. E. Cinner, M. L. Barnes, Social dimensions of resilience in social-ecological systems. *One Earth* **1**, 51–56 (2019).
40. D. H. Meadows, *Thinking in systems: A primer*, D. Wright, Ed. (Chelsea Green Publishing–Sustainability Institute, 2008).
41. A. D. Henry, B. Vollan, Networks and the challenge of sustainable development. *Annu. Rev. Environ. Resour.* **39**, 583–610 (2014).
42. M. Schlüter *et al.*, Capturing emergent phenomena in social-ecological systems. *Ecol. Soc.* **24**, 1–26 (2019).
43. W. Feng, E. F. Crawley, O. De Weck, R. Keller, "Dependency structure matrix modelling" in *12th International DSM Conference*, (Design Society, Cambridge UK, 2010), pp. 1–16.
44. D. Mustafa, D. Wrathall, Indus basin floods of 2010: Souring of a Faustian Bargain? *Water Altern.* **4**, 72–85 (2011).
45. A. R. Bell, M. A. A. Shah, A. Anwar, T. Sam, Crafting spaces for good water Governance in Pakistan. *Water Resour. Res.* **58**, 1–13 (2022).

46. A. Ilyas *et al.*, Balancing smart irrigation and hydropower investments for sustainable water conservation in the Indus basin. *Environ. Sci. Policy* **135**, 147–161 (2022).
47. P. Maji, N. E. Selin, A systems analysis of sustainability impacts of agricultural policies in India. *Earth's Futur.* **12**, e2023EF003667 (2024).
48. E. Ostrom, *Crafting Institutions for Self-Governing Irrigation Systems* (ICS Press, 1992).
49. J. L. Wescoat, Institutional levels of water management in the Colorado River basin region: A macro-historical geographic review. *Front. Water* **4**, 1024055 (2023).
50. Mathworks, Matlab. https://www.mathworks.com. 2022.
51. A. Siddiqi, Indus Basin HTE Network Modeling and Analysis Tool. In *Proceedings of the National Academy of Sciences*, vol. 121, p. 11. Zenodo. https://doi.org/10.5281/zenodo.10939384. Deposited 8 April 2024.