Social tipping points in global groundwater management

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Summary Paragraph

Groundwater is critical to maintain global food security, environmental flows, and millions of rural livelihoods in the face of climate change[1]. Although a third of Earth's largest groundwater basins are being depleted by irrigated agriculture[2], little is known about the conditions that would lead resource users to comply with groundwater conservation policies. To address this, we developed an agent-based model[3,4] of irrigated agriculture rooted in principles of human cooperation[5,6] and collective action[7], grounded on the largest dataset of cultural values in existence: The World Values Survey Wave 6 (n=90,350). Simulations of three major aquifer systems currently facing unsustainable demands—the Punjab (India/Pakistan), the Central Valley (USA), and the Murray-Darling Basin (Australia)—reveal tipping points where social norms and collective attitudes towards groundwater conservation shift abruptly with small changes in cultural values and enforcement provisions. We find that these tipping points are amplified by group size and most effectively invoked through group processes and social capital. Overall, our study presents a new powerful tool for groundwater management that can be used to evaluate how regulatory compliance is contingent upon cultural, socioeconomic, institutional, and physical constraints and conditions, and its susceptibility to change beyond thresholds. Managing for these thresholds may help avoid unsustainable groundwater development, reduce monitoring and enforcement costs, coordinate regulation of transboundary aquifers, and increase the resilience of communities to future drought and changes in regional climate. Although we focus on groundwater, our methods and findings and their usefulness in designing resource management plans and policies apply broadly.

Groundwater underpins humanity's resilience to water scarcity in a changing climate[1]. In the past decade, thousands of cubic kilometres of non-renewable groundwater storage have been lost to expanding irrigated agriculture in the world's major aquifers[2,8]. Infrastructure and economic solutions introduced to avert groundwater overuse have been unable to balance regional water budgets[2], whereas national groundwater laws and policies can take several decades to fully implement with no guarantees that resource users will adhere to them[9]. In developing nations, the challenge is far greater given the sheer number of users competing for the same limited resource. In these regions, farmers have few incentives to self-organise to secure future availability, and regulating individual pumping decisions is often logistically and practically impossible. Compliance with groundwater conservation policies is therefore essential to achieve socially acceptable, environmentally sustainable, and economically viable exploitation of aquifers that supply water and food to billions of people[10].

Conservation policies however are only means to promote compliance[11]. In collective action problems, as in those relating to the management of shared natural resources, human behaviour is deeply influenced by factors that sustain societal norms such as reputation, the possibility of punishment, and cultural values. Social norms, in fact, have been a key ingredient to achieve long-term collaboration between government authorities and water users[12-14]. Social norms are evolved behaviours maintained by social approval or disapproval that provide a shared benchmark to evaluate whether an action is appropriate. As yet, research has focused mostly on standard policies and instruments for securing groundwater availability[10] (e.g., monitoring, taxes, quotas, fines, etc.). A remaining challenge is to understand how people's attitudes towards groundwater conservation relate and respond to such instruments and how norms that either support or undermine compliance emerge from the strategic interactions of resource users. By focusing on the emergence of social norms, the framework we present here aims to place the debate on indirect and counterintuitive ways to trigger sustainable management outcomes from the bottom-up.

Three policy-relevant questions arise: Are rigorous monitoring and enforcement the only way to deter breaches and achieve compliance? What role do social norms and cultural values play here? And, in which countries is groundwater conservation more likely to succeed? To shed light on these questions, we devised the 'Groundwater Commons Game' (GCG)—an agent-based model[3,17] grounded in principles of human cooperation[18,19] and collective action[7,11,20]. Agent-based "artificial societies" offer a qualitatively different and unique approach to unravel the social, economic and environmental complexities and nuances of managing groundwater[16], in ways that would be impossible with field studies. Here, we study "artificial societies" of computational agents[4] that mimic the behaviours and interactions of groundwater users, and "grow" successful groundwater management scenarios *in silico*. Our model, for the first time, synthesises and extends existing work on the evolution of cooperation and collective action to elucidate possible determinants and pathways to regulatory compliance in groundwater systems globally.

We endowed our agents with culturally-varying parameters derived from the largest and most recent international study of human values and beliefs in existence—the World Values Survey Wave 6 (WVS6) (www.worldvaluessurvey.org). This is the first time such a large dataset is used to understand how culture impacts resource conservation at a global scale. We also employed grid-group theory[21], a robust framework used in cultural anthropology, to classify human societies and conceptualise four types of social organisation co-existing with different degrees of dominance in every society (hierarchist, individualist, fatalist and egalitarian, Fig. 1 and Extended Data Fig. 3). In our model, grid represents people's tolerance towards non-compliant behaviour (high grid less tolerant); whereas group represents how important it is for people to maintain a good reputation (high group more important). Our agents, much like in the real world, have limited information about groundwater conditions and what others are doing; yet they learn to cope with this uncertainty via heuristics and social interactions[22] (Supplementary Methods, Fig. 2, Extended Data Fig. 1).

We parameterised GCG models for the Murray-Darling Basin (Australia), the California Central Valley (USA), and the Punjab (India and Pakistan)—three culturally-diverse groundwater-dependent regions experiencing long-term depletion and representative of the four types of social organization, where significant irrigation water curtailments are needed to stabilise groundwater levels (Supplementary Methods). For generality, we considered groundwater conservation policies in their most simple form: a regulator that announces prescribed limits on pumping to licensed groundwater users, which are subsequently enforced through variable levels of monitoring (*M*) and fines (*F*). The regulator only has the capacity and resources to monitor a fraction of resource users. Groundwater users may comply (*C*) or defect (*D*) (i.e. extract groundwater illegally beyond the allocated limit). Users can report offending neighbours, or do nothing.

As shown in Fig.2, each agent has a unique strategy (*B,V*) representing its attitude towards groundwater conservation at a given point in time. Boldness (*B*) is the probability that the agent will defect; vengefulness (*V*) is the probability that the agent will report a non-compliant neighbour[6]. In our simulations, strategies undergo an evolutionary selection process, whereby agents rely on local information and operate on a simple heuristic to decide what do next: "*imitate* the strategy of whichever neighbour is doing best, *exploit* the current strategy if better, and *explore* a new strategy occasionally"[22]. Strategies are being continuously being evaluated based on the social and economic benefits and costs that they bring to each agent. In this dynamic setting, the emergence and evolution of social norms can be quantified as S = mean(V) - mean(B)[6]. Thus, a norm of compliance emerges[17] if the majority of agent strategies evolve to a cooperative state (B~0, V~1, S~1). The opposite is true for non-compliance if strategies evolve towards S~-1. The chosen strategies trigger pumping decisions that determine a specific level of regulatory compliance and impact on the groundwater resource (drawdowns); feeding back into the social dynamics as information for subsequent agent decisions. The agent model is coupled to a spatially-explicit groundwater flow model[16] (Supplementary Methods).

Our simulations show that pathways to effective groundwater conservation are controlled by tipping points, at which the degree of regulatory compliance becomes highly sensitive to contextual factors such as cultural values and enforcement provisions (Fig. 3a-c). These tipping points are defined by a transition zone with a specific location (its position within the grid-group cultural landscape), gradient (how steep the transition is) and shape (how its gradient varies across the cultural landscape). These three features define the boundary between two alternative states[24] of management: overuse and conservation. As in the socio-ecological system framework[25,26], these features provide the conceptual tools needed to establish a system's resilience (i.e., how likely and how quickly it will shift between overuse and conservation, and vice versa).

Grid and group size were major factors controlling the gradient and shape of tipping points. High-grid societies—where the social costs of reporting non-compliance are typically low[27]—exhibited more abrupt transitions compared to low-grid societies (Figs. 3a-c). Small, dispersed user groups responded almost linearly to cultural variability and enforcement provisions and did not develop particularly high or low levels of compliance (Fig. 3 and Extended Data Fig. 4, Murray-Darling Basin). By contrast, in large and highly connected user groups tipping points had steep gradients (Fig. 3 and Extended Data Fig. 4, Punjab). In these cases, on either side of the tipping point we found relatively stable areas of high compliance (conservation) and non-compliance (overuse), suggesting that strong social ties increase the stability of these states (i.e., small responses to small changes in conditions; the local resilience[25]). Three implications follow. First, conservation close to the threshold may give a false impression of stability, masking the risk that compliance norms may be actually approaching a tipping point. Second, overuse close to the threshold could give the false impression that achieving extraction targets would require significant time and resources, when only a small policy or cultural change may be sufficient. Third, large and densely-populated groundwater systems (when far from the tipping point) may require the investment of significant resources before noticeable increases in compliance are observed[9].

Mapping our GCG outputs across the grid-group cultural landscape and superimposing WVS6 statistics revealed (i) how identical management policies (Extended Data Fig. 4, rows) can produce vastly different outcomes in different societies (i.e., the relative locations of shaded regions for each specific country), and (ii) how cultural variability can lead to differences in compliance in a given society (i.e., the range of compliance outcomes possible within each shaded region). These results are consistent with empirical evidence[7,28] showing that accepted values of behaviour in a given community significantly affects the way local participants understand, implement, modify, or ignore rules imposed by institutions.

Next, we examined system-wide impacts of tipping points by assessing the social, economic and environmental performance of our artificial societies. Our results highlight how crossing a tipping point (e.g., traversing the dashed lines defining 50% compliance) can precipitate a systemic cascade across other system domains. For example, illegal extractions—despite increasing overall productivity—erode social norms, deplete groundwater storage, and intensify income inequality (Figs. 3d-o). The California Central Valley offers a current example: lax regulation has fuelled a surge in drilling and pumping activity causing wells to run dry, faster rates of depletion, diminished environmental flows, aquifer compaction, damage to irrigation infrastructure, and increasing farmer debt[15]. Systemic cascades are ubiquitous in groundwater basins around the globe[1,9]. Our framework provides a way to quantitatively and qualitatively assess how far these systems may be from transitioning back to conservation.

As shown in Fig. 3a-b, even if groundwater extractions were to be strictly monitored and enforced (M+F+), conservation policies would only be mildly successful in individualist and egalitarian societies (predominantly developed nations). In large, densely populated groundwater basins within fatalist and hierarchist societies (typically developing nations)—where compliance could hypothetically be as high as 90% (Fig. 3c)—monitoring and enforcing pumping restrictions on millions of private wells would be an extremely expensive and time-consuming endeavour[9,11].

We asked whether group processes, such as social capital[12], could be a more effective means to promote compliance from the bottom-up. We seeded our simulations with an increasing number of compliance advocates (i.e. agents representing community leaders with fixed strategies B=0; V=1) located randomly in space. Results showed that a small proportion of community leaders had a strong, non-linear, positive influence on group behaviour (Fig. 4). For a scenario of low monitoring and fines (M-F-) and low compliance, only 10%, 20% and 40% of advocates were needed to reach the tipping point in the Punjab, Murray-Darling Basin and Central Valley, respectively. Notably, social capital steepened tipping points in all three cases regardless of cultural context and group size (Fig. 4d-e-f). By contrast, introducing more rigorous monitoring and fines (M+F+) did not have such effect (Extended Data Fig. 4). These results emphasise the potential benefits of leveraging norm formation processes to foster rapid transitions from overuse to conservation. Our analysis suggests that social capital can be particularly effective in large, densely populated groundwater basins in the developing world, where the connectedness of groups can amplify the spread of social norms at tipping points[24], as well as the stability of the conservation once the tipping point is crossed (Fig. 4). Evidence of successful management based on leadership and norms in countries like India and Pakistan[14] supports this observation.

To confirm the robustness of our conclusions, we compared results of GCG simulations with a unique field survey of water licensees conducted by the authors across three jurisdictions of the Murray-Darling Basin[23] (N=672, Supplementary Methods, Extended Data Fig. 6, Extended Data Table 2). Results for the Murray-Darling Basin based on WVS6 statistics were consistent ($P<0.001$) with grid, group and compliance measured in the field, thus providing empirical support and validity to our analysis.

What, then, can be done to develop groundwater conservation policies well-suited to the social, economic, political and environmental context of a given country or community? Based on our findings, we propose a three-stage approach. First, diagnose whether the system is close to its tipping point and assess how hard it would be for management to drive the system to the conservation state (i.e., based on the gradient and shape of the tipping point, as revealed by the GCG). Second, weave social capital to bring the system to the tipping point. Third, ensure compliance well past the tipping point to build system resilience. In other words, once sufficient interest in rule adherence has been created and norms begin to emerge, little effort in monitoring and enforcement may be required to reach and maintain sustainable conservation targets. Effective and enduring compliance with such targets can significantly increase the ability of communities to maintain agricultural yields through future droughts and changes in regional climate[1].

The Groundwater Commons Game (GCG), allows a new approach to systematically quantify the proximity, steepness and shape of social tipping points and where managed groundwater systems might sit with respect to them. We show how the WVS6—heretofore confined to social research—can enrich our understanding of commonalities and barriers to implementing conservation policies in groundwater depletion hotspots where curbing demands is critical for sustainability[2,8]. Overall, the GCG offers a useful framework for identifying, early in the planning process, where and when to target management efforts to balance the environmental, economic, and social implications of these policies. This information is critically important considering that groundwater management is politically challenging, time consuming, and expensive to implement and enforce[1,10]. These aspects are exacerbated in the case of transboundary aquifers (e.g., India-Pakistan, Mexico-USA, Brazil-Argentina, see Fig.1), where resources are shared across cultural borders[9,29]. Our methodology, for the first time, reveals the relative “location” of nations within the space of possible societal responses to transboundary aquifer management. Last, because our modelling framework is flexible and can be coupled to any environmental model, our methods can be applied to other resource systems where regulatory compliance is critical to sustainability, such as fisheries, forests, wildlife and global climate.

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Author Contributions

J.C.C., R.R. and G.M. developed the research ideas and designed the study; C.H. conducted the Murray-Darling Basin water license surveys; J.C.C. implemented the model, performed computational experiments, prepared figures, and analysed the World Values Survey data. All authors contributed to the analysis, interpretation, figure design, and writing.

Author Information

The authors declare no competing financial interests. The data, agent-based model and code for statistical analyses are stored in [we will provide a link to a CSIRO data repository]. Correspondence and requests for data and materials should be addressed to J.C.C. (juan.castilla@csiro.au).

Supplementary Methods

Grid-group theory and the WVS6. *Grid* represents a society or group's reliance on standards (e.g., customs, morals, shame) for achieving goals. Low grid people have a desire for nonconformity and a belief that nonconformist behaviour leads to individual success. High grid people rigidly adhere to social norms; they are more willing to punish actions that violate these norms, even if it generates no direct benefits to them[27,30]. *Group* represents how strongly people in a society are bonded together. Low-group people are self-focused and competitive; high-group people have their interests overlapping with the interests of the collective. Together, grid and group form a two-dimensional representation of cultural types, split into quadrants that define four general typologies of human behaviour: individualist, egalitarian, fatalist, and hierarchist (Fig. 1). Grid and group dimensions were used as parameters in our agents' objective function (see below).

Although there are many large data sets that can be used to investigate cultural and value differences, the most often used is the WVS. Raw data (publicly available at www.worldvaluessurvey.org) is obtained through detailed questionnaires in face-to-face interviews. Questionnaires for the WVS6 (2010-2014) consist of 258 questions. In each country, the questionnaires are administered to about 1,000 to 3,500 interviewees, with a worldwide total of 90,350 interviews. We applied the methodology proposed by Chai et al.[27] to compute for the first time, to our knowledge, grid and group indices for the 57 countries covered by the WVS6 (Fig. 1, Extended Data Fig. 3).

We selected 10 grid questions and 10 group questions from the WVS6, covering as many social dimensions as possible. These questions were chosen based on a higher variation across nations when compared to other questions. We normalised the answers to each question to a scale from 0 to 1 to avoid inconsistencies in the arrangement, scale, and the quantitative/qualitative nature across WVS questions. We then computed country-level grid and group scores by aggregating individual responses under the two themes. We used even weighting to combine grid and group questions into a single score. This avoided introducing weight coefficients without clear justification. Even weighting is also used in a number of well-known social indexes, such as the Happy Planet Index (http://happyplanetindex.org) and the Human Development Index (http://hdr.undp.org/en). One-way analysis of variance (ANOVA), for all questions presented in Extended Data Table 2, shows that computed grid and group scores exhibit significantly less variance within societies than between societies ($P<0.001$). Our indices thus provide sufficiently large variation to highlight differences between countries.

Agent-based model. For our three case studies and for each possible combination of grid and group scores (9 grid scores x 9 group scores = 81 combinations), we initialised 100 'unregulated' (*M*=0, *F*=0) runs with random agent strategies. The groundwater model was set up using hydrogeological parameters characteristic of regional flow conditions in alluvial settings (see below). In each run, and after a 50-year burn-in period, we activated groundwater management scenarios (setting *M,F*≠0) with allocations arbitrarily set at 20% (to represent an extreme scenario of groundwater conservation). This assumption also reflects the fact that it is politically challenging to implement regulations in the real-world, and once regulations are introduced they are often hard to adjust over time. We then simulated the evolution of the system over 50 years. To account for uncertainty and stochasticity, we report the mean and standard deviation of 100 independent realisations.

The coupled agent-based groundwater model was developed using FlowLogo[16] (Extended Data Fig. 2), a software platform developed by the authors specifically for this purpose. The groundwater sub model represents a 10x10 km basin, discretised into 40x40 cells. The dimension of each cell is 200 m. Model boundary conditions are defined by a no-flow boundary to the North and South, and constant head boundary cells to the East and West; setting head values to create an East-West gradient of 1/1,000 representing typical conditions in regional aquifer systems. Underlying this basin is a semi-confined sand aquifer of 50 m thickness, hydraulic conductivity K=10 m/d and storativity S=1e-4. The model is transient with a time step of six months. We used a steady-state run with no pumping stresses as the initial condition for each simulation.

Agent objective function. Agents had the same objective function, which they used to evaluate the social and economic implications of their actions. This utility function combined: an economic score (*E*) that quantifies the gross margins of crop production, considering pumping costs based on local groundwater drawdowns; an institutional score (*I*) that notionally represents the proportion (0-100%) of gross margins forgone to pay fines; and a social score (*S*) that notionally represents the loss of reputation (proportional to group) and the social costs of reporting offenders (inversely proportional to grid). These components were combined into an overall performance index $PI=E*I*S$, which agents used to compare and decide among competing strategies. We generated this index based on equal weighting of *E*, *I* and *S*, as there was no theoretically a priori reason to assign one variable greater importance than another.

Economic score (*E*). We assumed that prior to regulation, farmers irrigate crops at full nominal water requirement (Extended Data Table 1). For simplicity, we also assumed that farmers do not engage in deficit irrigation, meaning that under pumping restrictions they are forced to reduce their irrigated acreage. If a farmer cooperates, it only irrigates a fraction of land equivalent to the pumping allocation (i.e., if the allocation is 20% of the full license, the farmer irrigated 20% of his land). If the farmer defects, it pumps a fraction of illegal water proportional to his boldness. For example, for a 20% allocation, a defecting agent with boldness B=0.1 would irrigate 20%+80%*0.1=28% of his land; one with boldness B=0.8 would irrigate 20%+80%*0.8=84% of his land, and so on.

We calculated gross margin budgets (Extended Data Table 1) using reported and published agro-economic statistics for Bollgard II R cotton in the Murray-Darling basin (2015 Australian Cotton Production Manual, http://www.cottoninfo.com.au/publications), almonds in the southern Central Valley (UC Davis Agricultural and Crop Economics; http://coststudies.ucdavis.edu), and the wheat-rice rotation in the Punjab[31,32]. Gross margins were calculated as total revenue minus total costs, not including the energy costs of pumping groundwater. Pumping costs were calculated and incorporated to the agent objective function at simulation runtime using depths to water table from the groundwater sub model, based on the following relationship for the power consumed by a centrifugal pump set:

$$PC = \frac{P_e g(WR)H}{\eta}$$

where *PC* is the pumping cost in US$/ha, *Pe* is the price of electricity in US$/kWh, g is gravity, *WR* is the crop's water requirement in ML/ha, and *H* is the dynamic pumping lift of the pump in m.

Institutional score (*I*). Notionally represents the proportion of gross margins forgone to pay fines when an agent is caught breaking the rules, according to the relationship:

$$I = \begin{cases} 1, & if\ an\ audited\ farmer\ cooperated \\ 1 - F, & if\ an\ audited\ farmer\ was\ caught\ defecting \end{cases}$$

Social score (*S*). The social performance of each agent was quantified using the following relationship:

$$S = (1 - grid)^m group^n$$

where m is the number of breaches that an agent chooses to report to the regulator; n is the number of neighbours that detect an offence in any given year.

Murray-Darling Basin validation surveys. To test the validity of the GCG in a real-world groundwater management scenario, we computed indices for grid group (see Extended Data Table 3), monitoring (*M*), fines (*F*), and compliance from a quantitative survey of approximately 4000 water license holders (22% response rate) conducted by the authors between September 2012 and January 2013 in New South Wales, eastern Australia[23]. Our survey captured water users' views on compliance motivations, experiences with compliance and enforcement by the New South Wales Office of Water, water users' information sources, and their knowledge of water regulation.

Grid and group indices computed from our surveys do not differ significantly from indices obtained from the WVS6 (t-test; n_{WVS}=1477 and $n_{MDBsurvey}$=672; two-sided P=0.12 for grid and P=0.65 for group). Empirical values for monitoring (*M*), fines (*F*), and compliance were obtained from survey questions 'q2off' ("compliance officers from the New South Wales Office of Water work regularly in my region") and 'q3pro' ("people illegally taking water will be prosecuted"), 'q3det' ("the penalties for illegal water extraction are a strong deterrent") and 'q3crim' ("getting a criminal record for carrying out illegal water activities is a strong deterrent"), and 'q3big' ("illegal water extraction is a big problem in my region"), respectively. Observed compliance was consistent with our simulations (see Extended Data Figure 6).

Main Text Figures

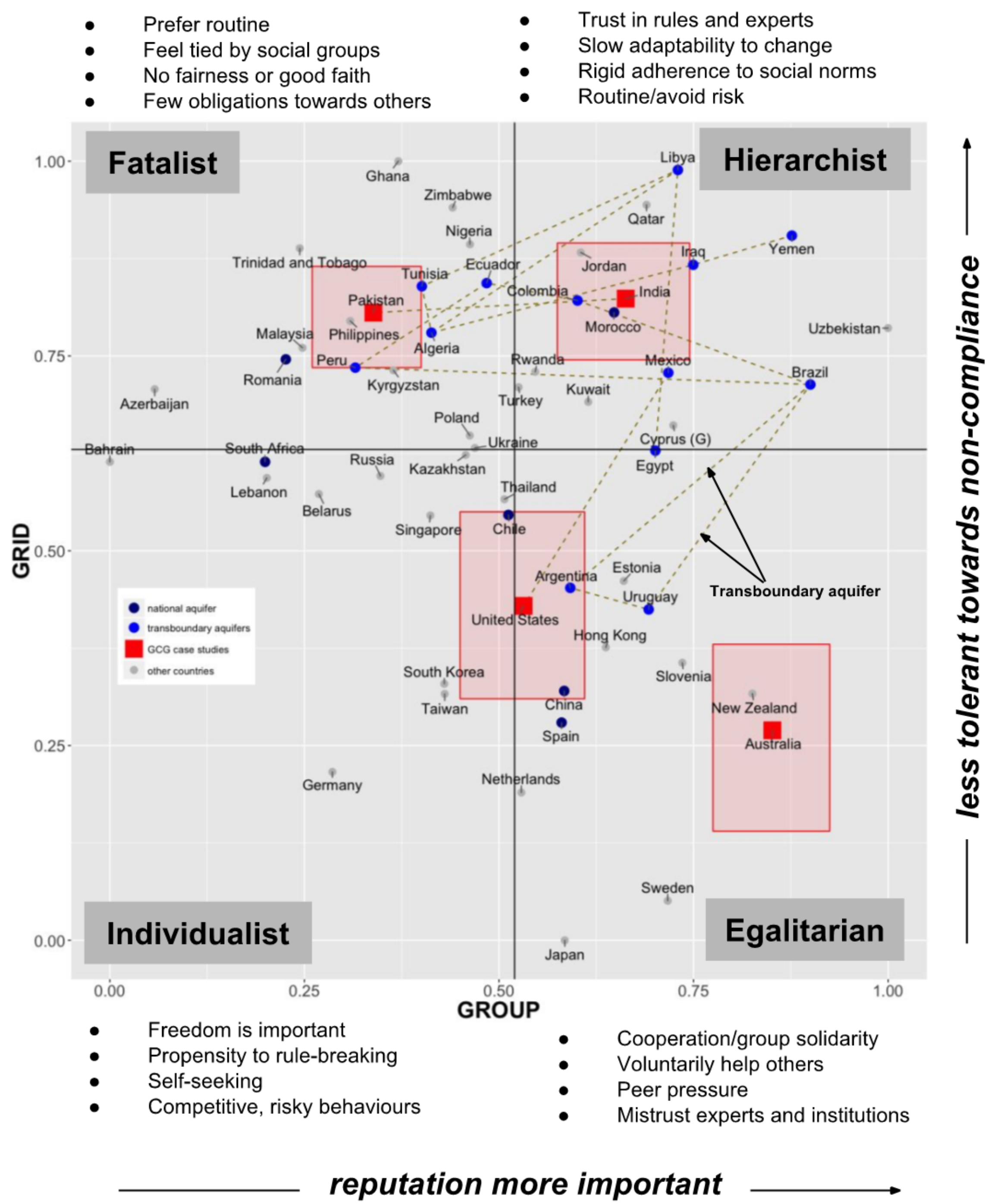


Figure 1 | World Values Survey 6 statistics reveal countries where groundwater regulation is more likely to succeed. Grid and group means are shown for case studies (red) and countries with transboundary (blue) and national (dark blue) aquifers of agricultural importance[2,8]. Other countries (grey) are presented to emphasize geographic and socioeconomic correlations. Boxes indicate grid and group interquartile ranges, horizontal and vertical lines grid and group averages, respectively. Tipping points are aligned along the fatalist-egalitarian transect, becoming steeper with increasing grid and group size (Fig. 3a-c, Extended Data Figure 5). Dashed lines show important transboundary aquifer relationships. To enhance cultural contrasts, we normalised grid and group using minimum and maximum mean scores of the cohort (Extended Data Fig. 3).

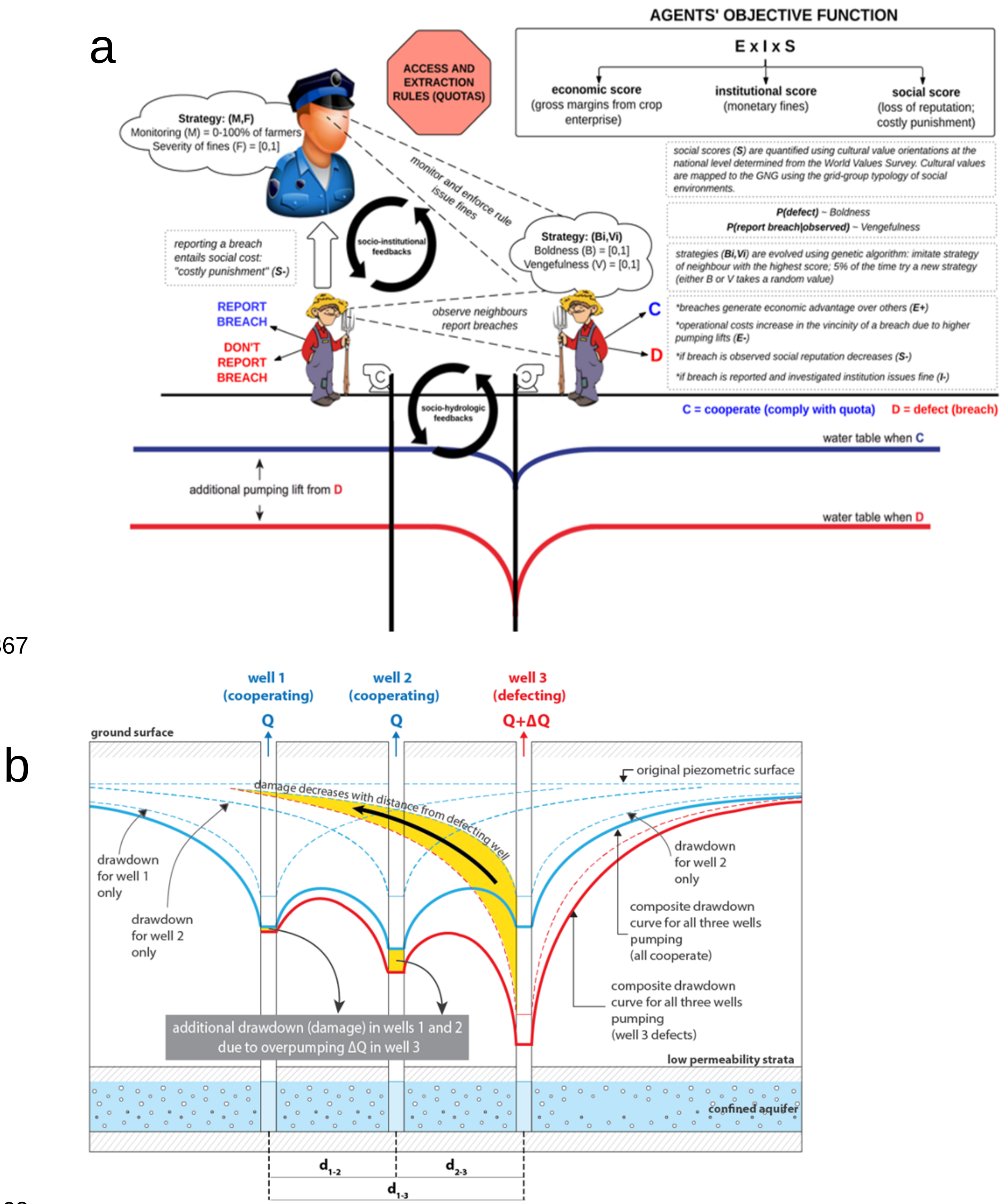


Figure 2 | The Groundwater Commons Game. (a) Farmers are placed in the spatial context of a groundwater irrigation area and make decisions on their groundwater pumping according to current groundwater resource conditions (water levels and cost of pumping), the water allocations, their personal and their cultural, socio-economic context. Agents face the decision of whether to cooperate with the allocations (withdraw a fraction of their license as required by the regulator) or to defect (withdraw more than the allocation to increase profits). (b) Breaches impose higher economic costs to other agents, due to the widening and deepening of pumping cones of depression.

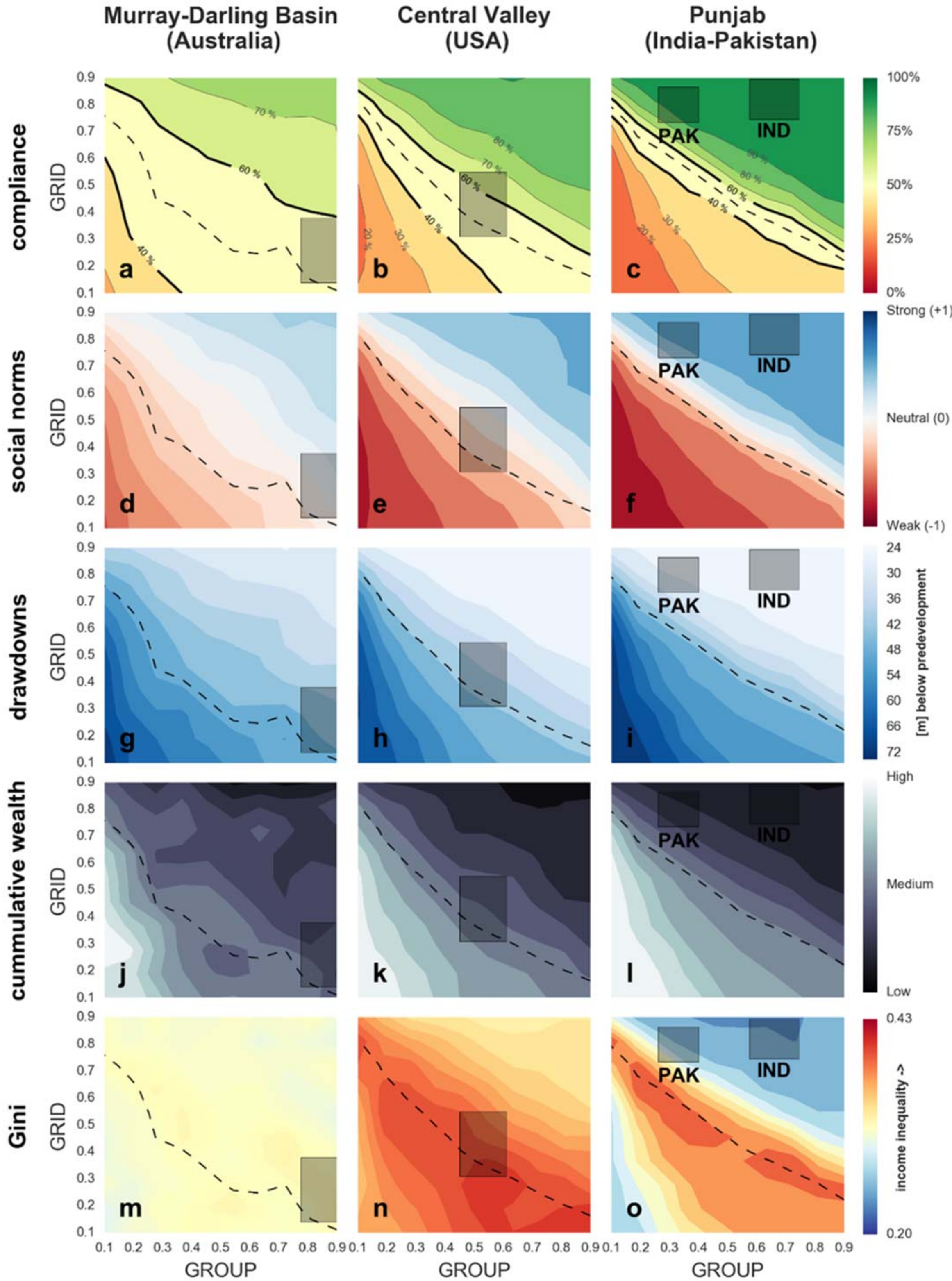


Figure 3 | Crossing compliance thresholds can trigger cascades across system domains. The GCG reveals trade-offs between social (d-f), environmental (g-i), and economic (j-o) objectives, and helps assess where a system sits with respect to its tipping points (a-c). Dashed lines indicate 50% compliance, dark lines 50+-10% compliance. Shaded boxes indicate grid and group interquartile ranges obtained from the WVS. Results (mean of 100 realisations for each parameter combination) are shown for M+F+.

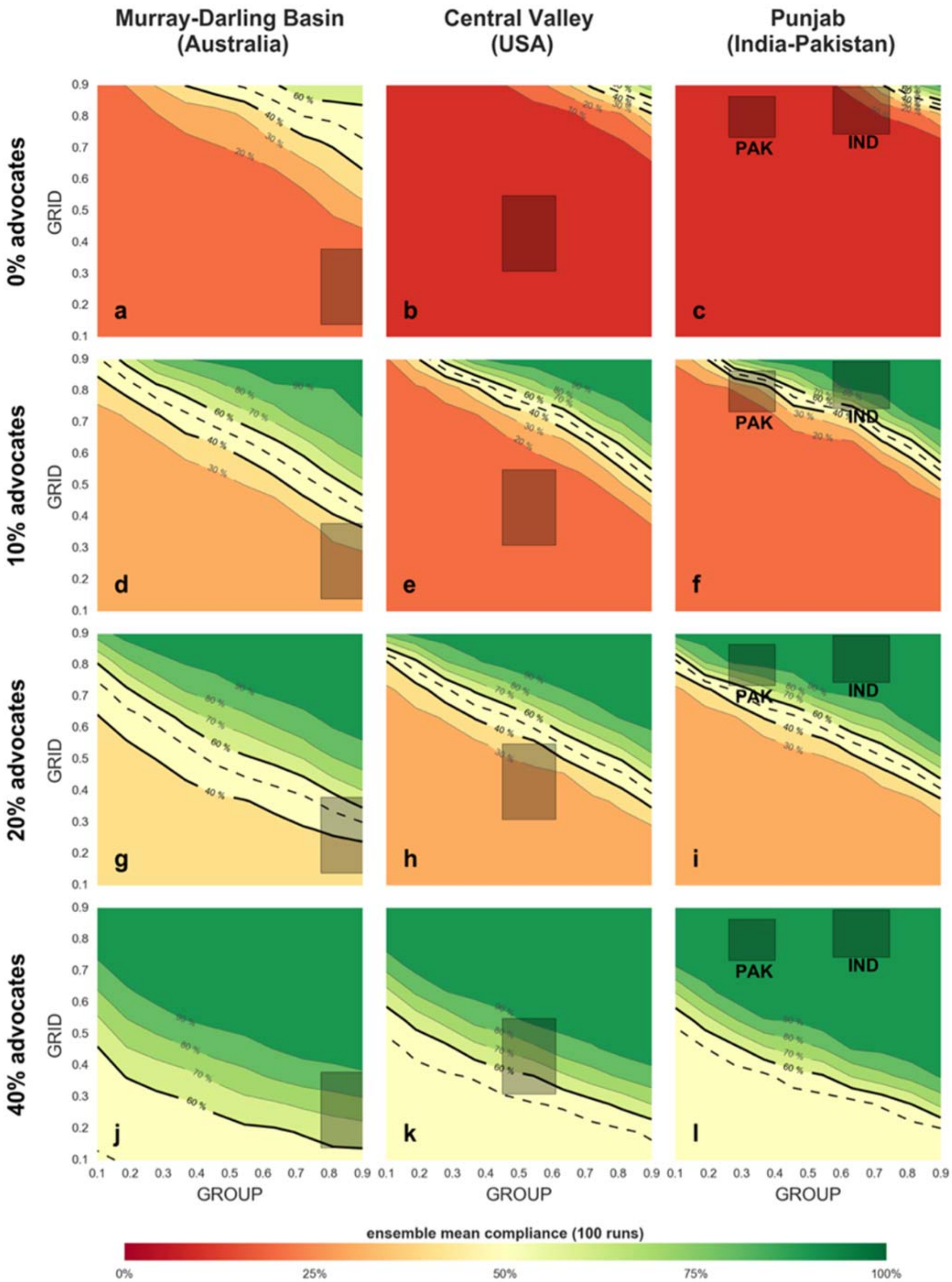
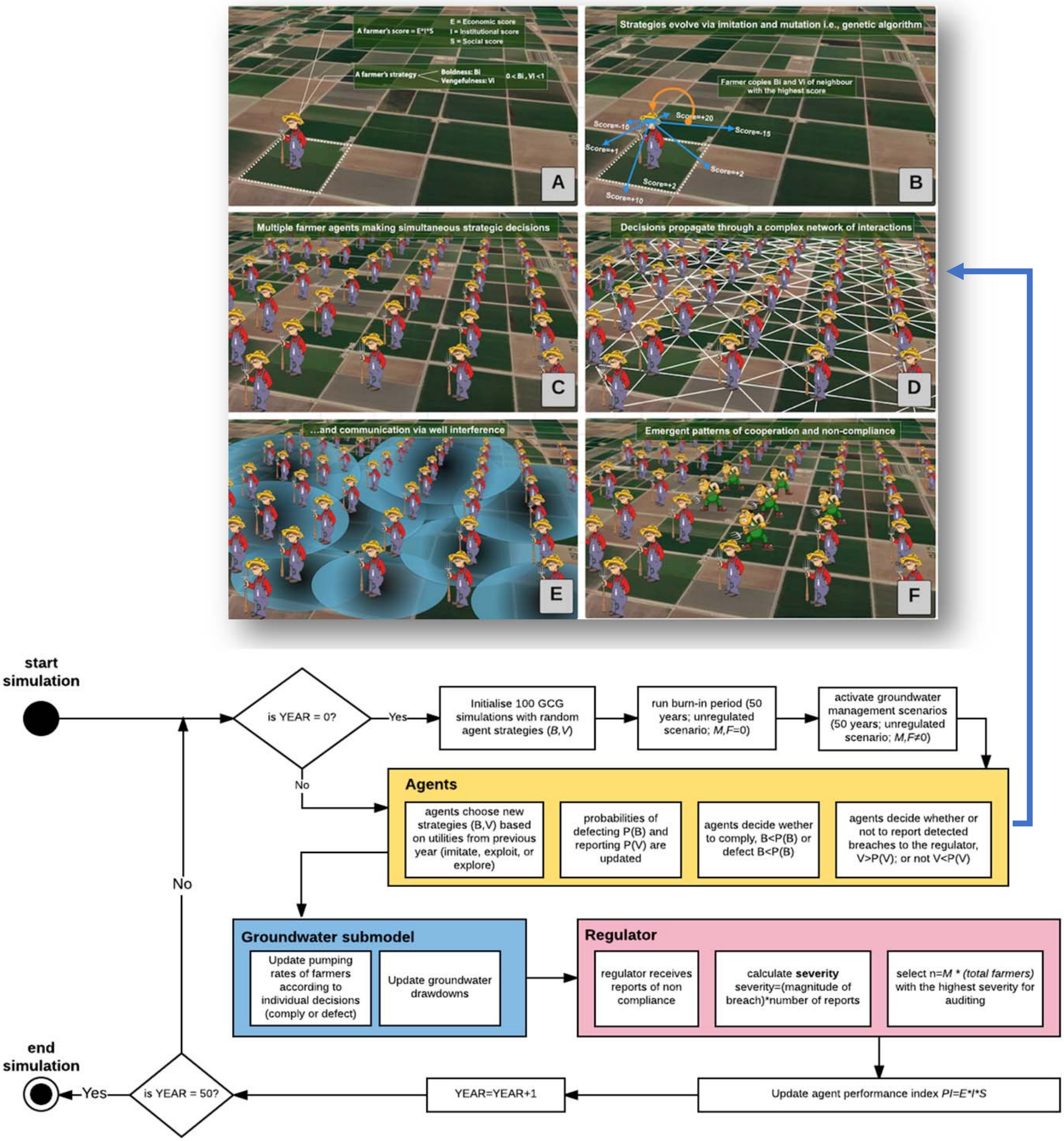
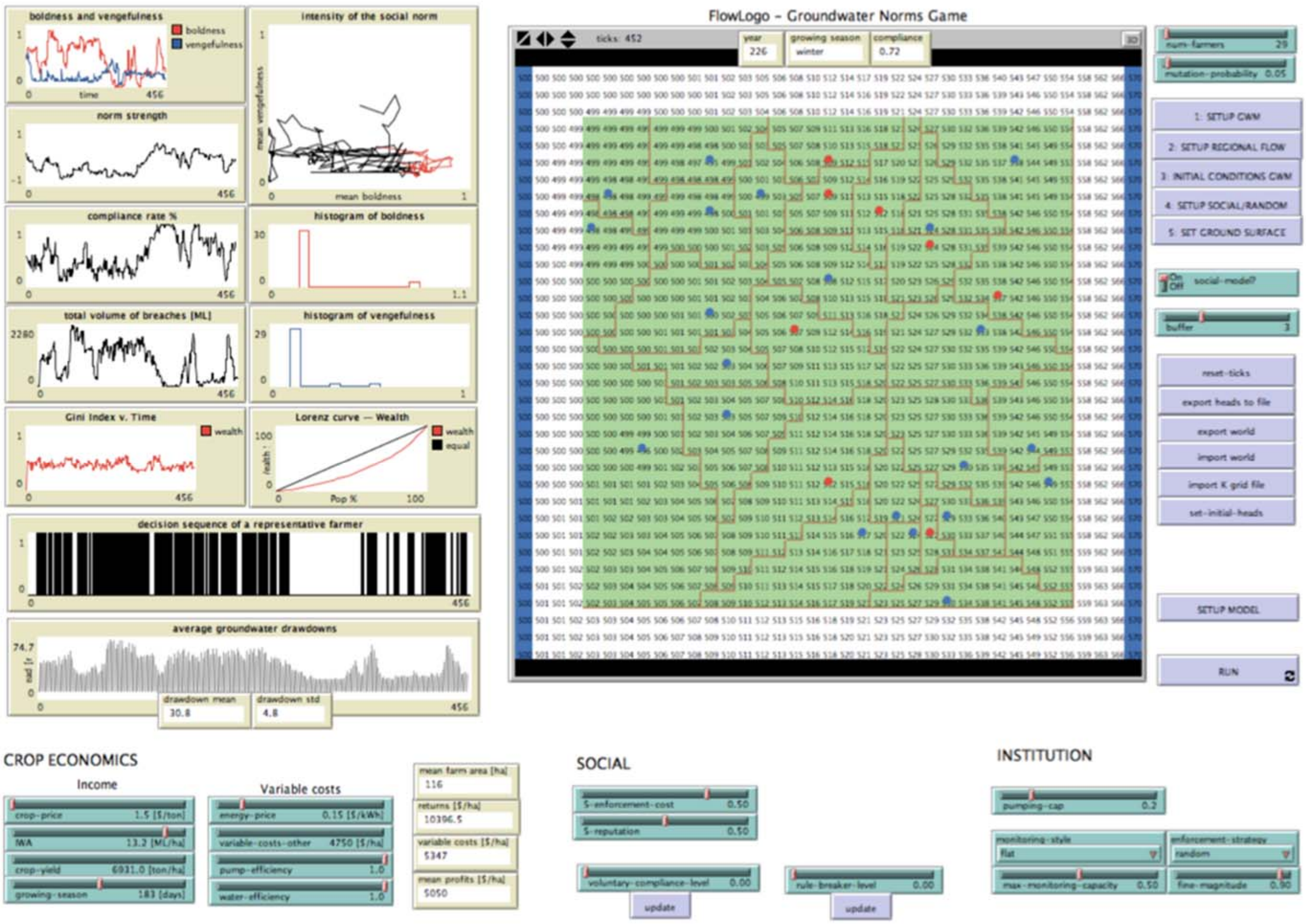


Figure 4 | A minority of community leaders has a strong positive influence on compliance and the attainment of groundwater conservation targets. Unlike monitoring and fines (Extended Data Figure 5), social capital exerts a strong and positive influence on all three features of tipping points: it encourages steeper transitions to compliance states, and builds resilience (regions of high compliance become wider, the system moves away from the tipping point). Results shown for a scenario of weak regulation (M-F-).

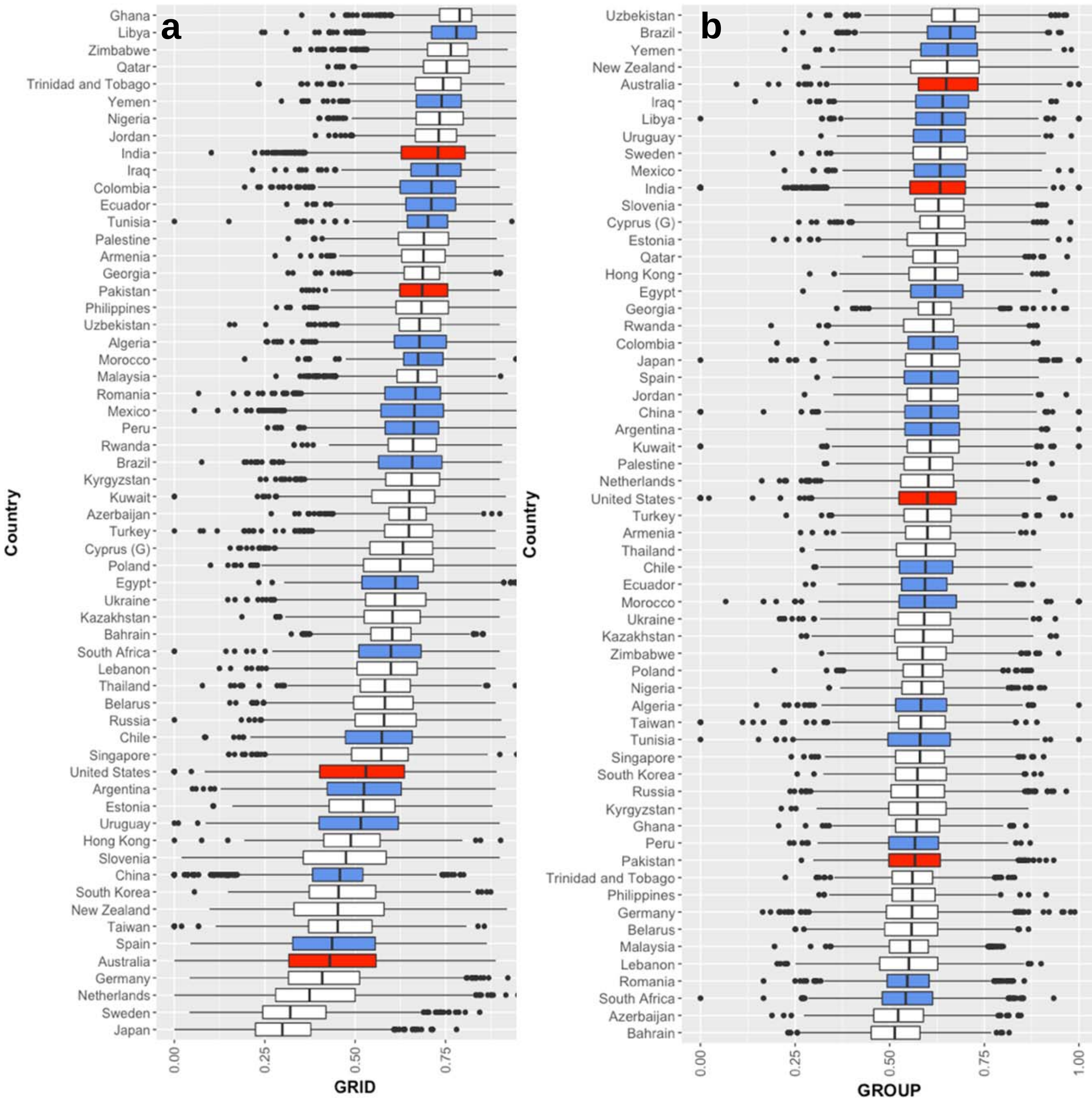
Extended Data Figures



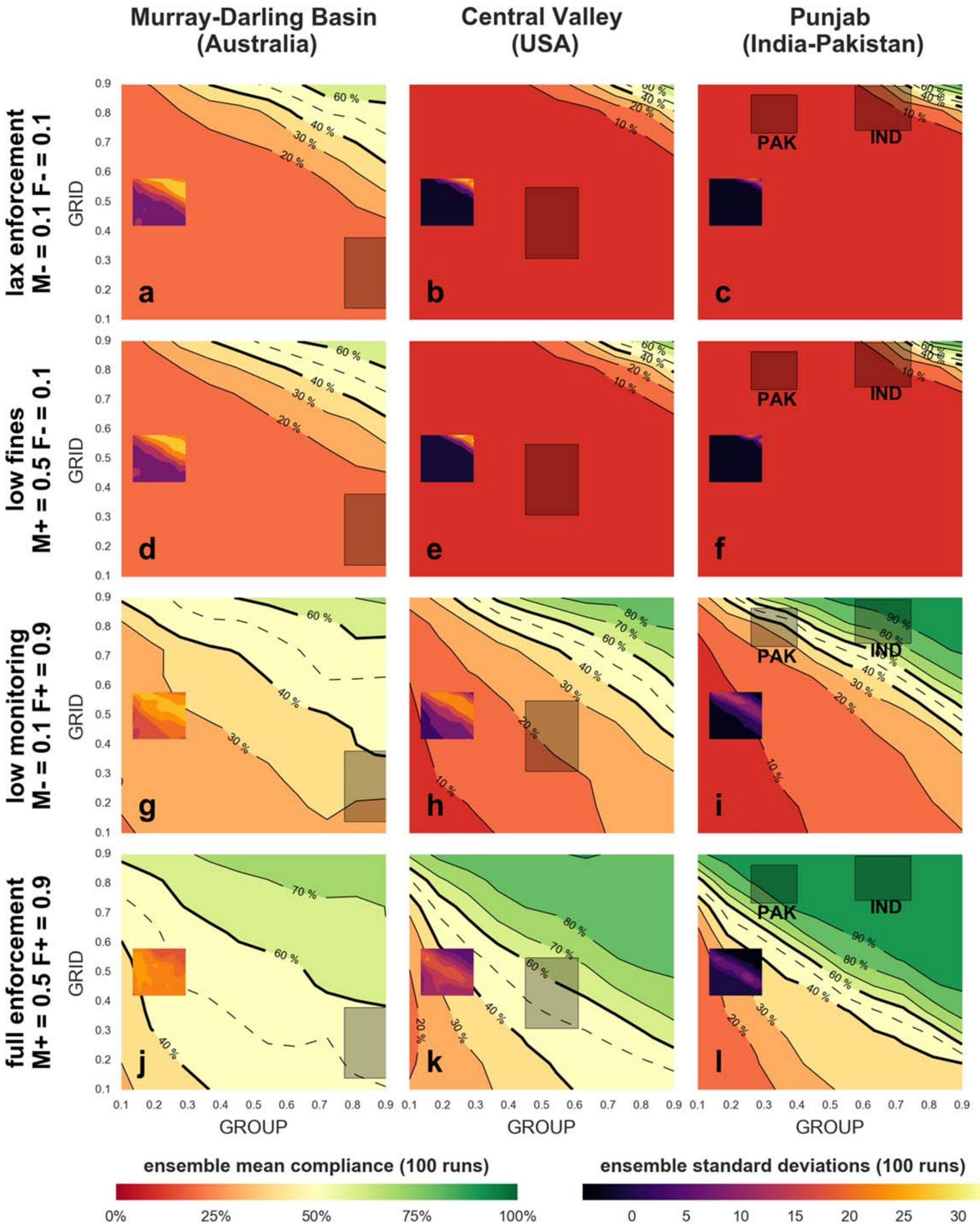
Extended Data Figure 1 | GCG main processes. (top) schematic of agent dynamics (bottom) scheduling of agent and groundwater processes.



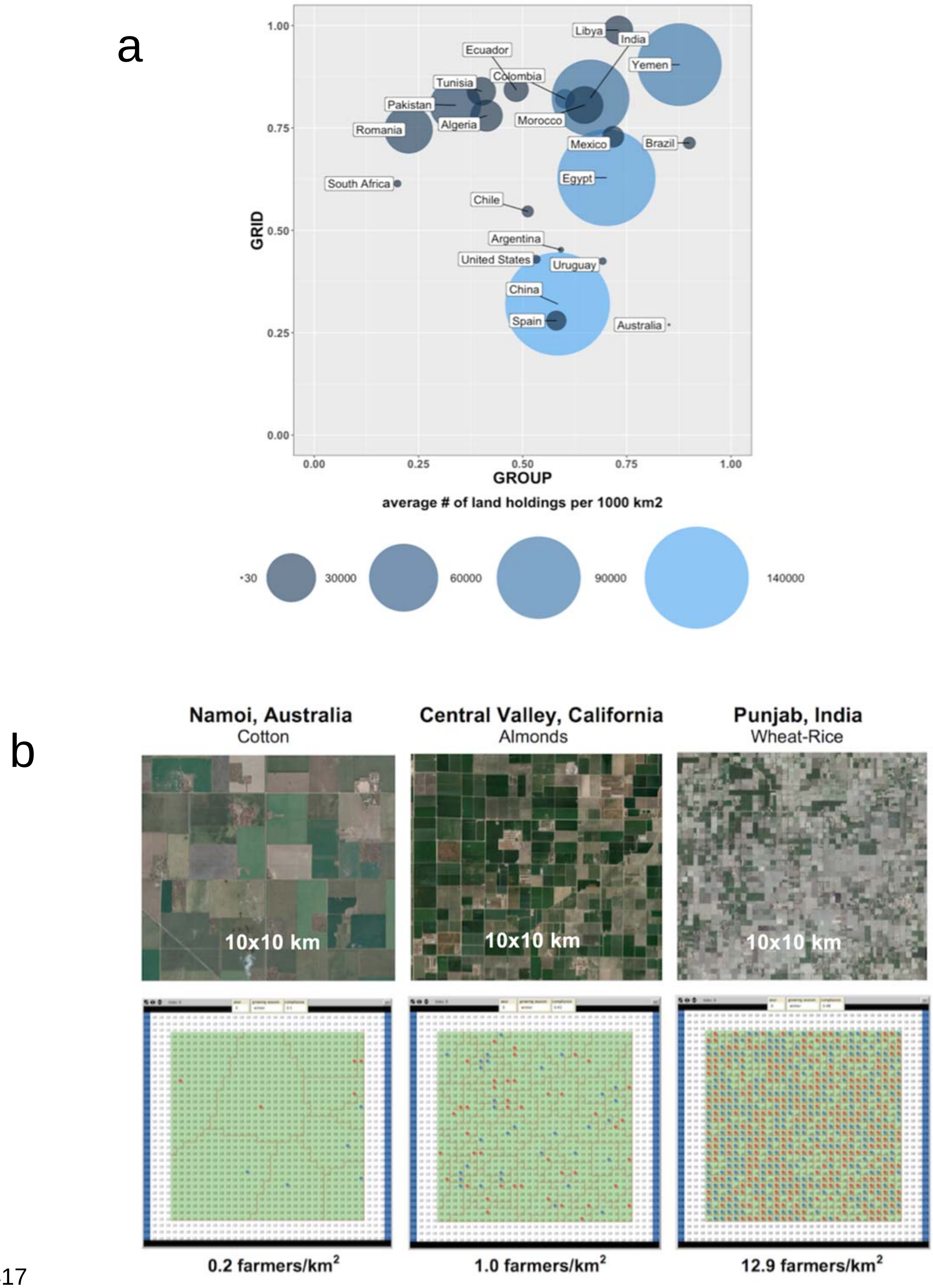
Extended Data Figure 2 | Agent-based implementation of the GCG. User interface for one of our case studies. Model window shows time series and histograms coupled social-groundwater output; sliders and switches to set base parameters for agents; controls for cultural variables and policy intervention mechanisms.



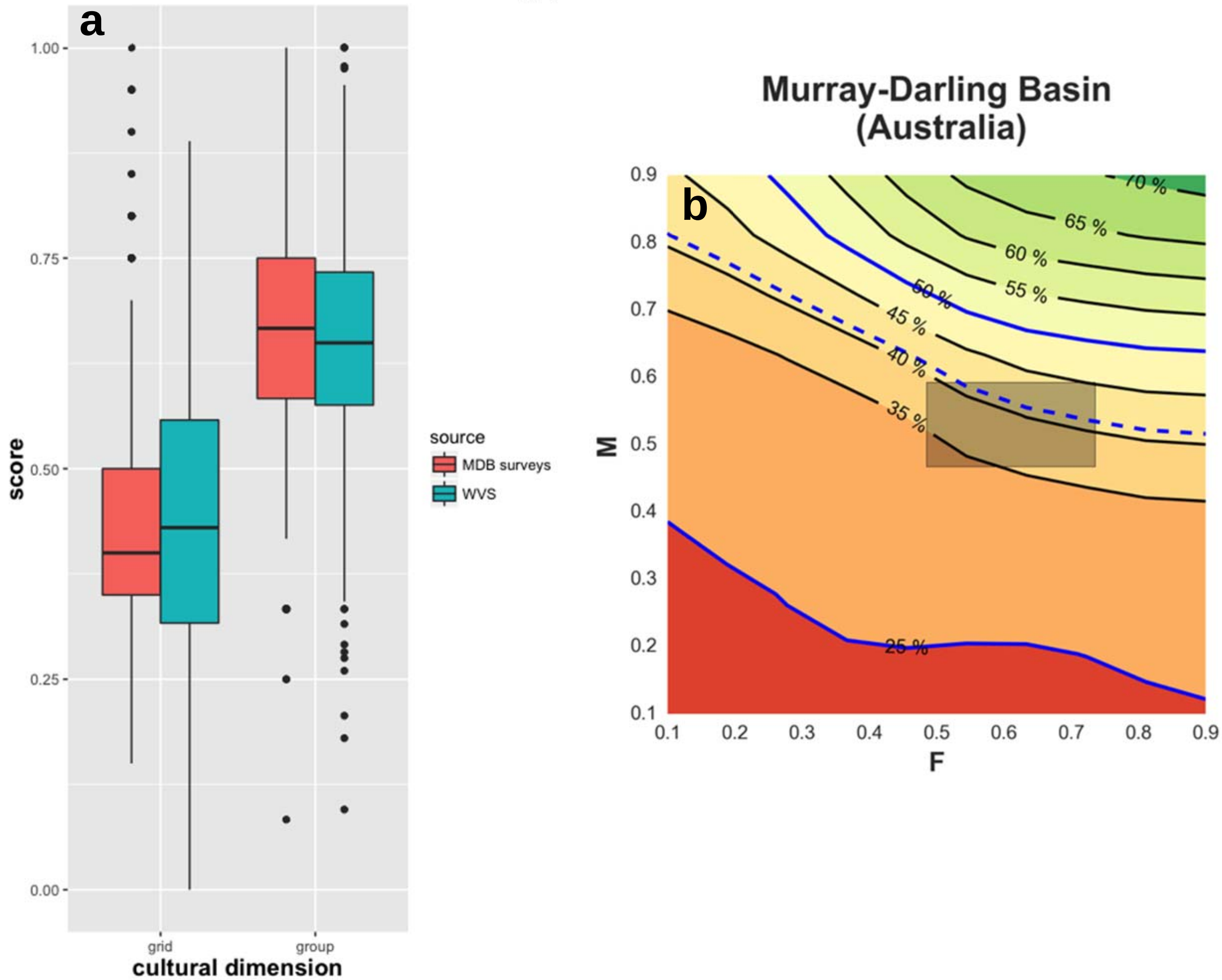
Extended Data Figure 3 | World Values Survey 6 grid-group summary statistics. (a) grid scores, (b) group scores. Countries with aquifers of national or transboundary importance (blue), case studies (red), other countries (white).



Extended Data Figure 4 | Enforcement provisions (monitoring and fines) mostly control the location of tipping points. Columns correspond to our three case studies, ordered from left to right according to increasing group size. Rows show increasing enforcement provisions (M=monitoring; F=fines). Shaded boxes show grid and group interquartile ranges obtained from the World Values Survey Wave 6. Contours indicate % compliance with groundwater conservation policies. Insets show ensemble standard deviations of 100 independent realisations.



Extended Data Figure 5 | Representative group sizes for countries with aquifers of national or transboundary importance. (a) average land holdings computed from FAOSTAT (http://www.fao.org/faostat/en/#home). (b) GCG implementation of group size effects. Top panels show typical spatial distributions of land holdings in a 10x10 km region from Google Earth Imagery. Bottom panels show corresponding agent-based representations. See Extended Data Table 1 for agro-economic data used to parametrise GCG simulations in each case.



Extended Data Figure 6 | Murray Darling Basin surveys are consistent with WVS6 statistics and GCG simulations. (a) grid and group statistics from the WVS6 did not differ significantly (t-test, two sample P=0.12 for grid and P=0.65 for group) from scores computed from our surveys in eastern Australia. (b) Comparison of observed (our surveys) and GCG-simulated compliance. Black contours indicate GCG outputs across M-F space. Solid blue lines indicate interquartile range, and the dashed line the mean from our surveys. Shaded box shows interquartile range for M and F obtained from our surveys (see Supplementary Methods).

Extended Data Tables

Extended Data Table 1 | Agro-economic data for the three case studies.

	Australia	United States	India-Pakistan	
Representative region	Murray-Darling Basin (Lower Namoi)†	Southern San Joaquin Valley‡	Punjab§	
Crop	Bollgard R II cotton	Almonds	Rice	Wheat
Average farm size	362 ha	74 ha	4 ha	4 ha
Yield	10.5 bales/ha	6930.7 lb/ha	6960.0 kg/ha	5525.0 kg/ha
Price	580 AUD/bale	1.5 USD/lb	0.11 USD/kg	0.12 USD/kg
Revenue	6090 AUD/ha	10396 USD/ha	766 USD/ha	663 USD/ha
Total costs	3395 AUD/ha	6101 USD/ha	411 USD/ha	216 USD/ha
Costs of irrigation	570 AUD/ha	1351 USD/ha	89 USD/ha	27 USD/ha
Irrigation water requirement	9.5 ML/ha	13.2 ML/ha	13.52 ML/ha	4.1 ML/ha
Electricity price	0.20 AUD/kWh	0.15 USD/kWh	0.016 USD/kWh	0.016 USD/kWh
Total costs minus irrigation	2825 AUD/ha	4750 USD/ha	322 USD/ha	189 USD/ha
Gross margin*	3265 AUD/ha	5646 USD/ha	444 USD/ha	474 USD/ha

* gross margins do not include electricity pumping costs (computed at runtime, based on drawdowns obtained from the groundwater submodel)
† 2015 Australian Cotton Production Manual; http://www.cottoninfo.com.au/publications
‡ UC Davis Agricultural and Crop Economics; http://coststudies.ucdavis.edu
§ see[31,32]

Extended Data Table 2 | Grid-Group categories and one-way analysis of variance (ANOVA) for the World Values Survey Wave 6

Cultural dimension	Variable	question code	Value orientation question	High	Low	Mean	SD	F-value*
GRID	**Grid 1**	V9	*Religion*	Important	Not important	0.71	0.35	820.7
	Grid 2	V164	*Job old/young*	Old acceptable	Old unacceptable	0.44	0.30	44.8
	Grid 3	V21	*Follow instructions*	Yes	Not necessary	0.41	0.49	79.3
	Grid 4	V69	*Respect authority*	Yes	No	0.74	0.35	402.4
	Grid 5	V152	*Religion (God)*	God important	Not important	0.75	0.33	114.5
	Grid 6	V203	*Justifiable: homosexuality*	Never justifiable	Justifiable	0.75	0.34	52.8
	Grid 7	V203A	*Justifiable: prostitution*	Never justifiable	Justifiable	0.80	0.28	69.2
	Grid 8	V204	*Justifiable: abortion*	Never justifiable	Justifiable	0.75	0.31	337.3
	Grid 9	V200	*Justifiable: stealing property*	Never justifiable	Justifiable	0.09	0.20	403.6
	Grid 10	V77	*Behave properly; avoid doing anything people would say is wrong*	Very much like me	Not at all like me	0.69	0.27	179.6
GROUP	**Group 1**	V4	*Importance: Family*	Important	Not important	0.97	0.12	428.1
	Group 2	V5	*Importance: Friends*	Important	Not important	0.77	0.25	46.2
	Group 3	V24	*Trust people*	Most can be trusted	Have to be careful	0.25	0.43	53.5
	Group 4	V71	*Importance: money*	Less emphasis	More emphasis	0.55	0.31	110.1
	Group 5	V98	*Responsibility: personal/government*	Government	Personal	0.61	0.32	85.5
	Group 6	V20	*Being unselfish*	Mentioned	Not mentioned	0.34	0.47	105.4
	Group 7	V74	*Doing something for society*	Very much like me	Not at all like me	0.70	0.25	26.6
	Group 8	V78	*Looking after the environment*	Very much like me	Not at all like me	0.70	0.26	50.0
	Group 9	V216	*I see myself as an autonomous individual*	Strongly disagree	Strongly agree	0.36	0.32	104.8
	Group 10	V213	*I see myself as part of my local community*	Strongly agree	Strongly disagree	0.74	0.27	260.4

*All the between-country F-values are significant at p<0.001

Extended Data Table 3 | Grid-Group categories and indexes for our Murray-Darling Basin surveys

Cultural dimension	Variable	Value orientation question	High	Low	Table*	question code	question mapping	survey score	normalised score	question score	GCG score
	Grid 1	*Complying with water laws is the right thing to do*	Strongly agree	Strongly disagree	4.1	q3law	Grid +	4.28	0.82	0.82	
	Grid 2	*Water regulation is needed to sustainably manage water resources*	Strongly disagree	Strongly agree	4.2	q1sus	Grid -	4.16	0.79	0.21	
GRID	**Grid 3**	*Water regulation is needed to protect the rights of water users*	Strongly disagree	Strongly agree	4.2	q1pro	Grid -	4.14	0.79	0.22	**0.433**
	Grid 4	*Water regulation is needed to protect the long-term viability of communities*	Strongly disagree	Strongly agree	4.2	q1com	Grid -	4.20	0.80	0.20	
	Grid 5	*Justifiable: illegal taking of water under tough economic conditions*	Strongly disagree	Strongly agree	4.4	q3ill	Grid -	2.13	0.28	0.72	
	Group 1	*Complying with my licence conditions is important because breaking the rules is unfair to other water users*	Strongly agree	Strongly disagree	4.1	q3lic	Group +	4.23	0.81	0.81	
GROUP	**Group 2**	*Complying with my licence conditions is important because breaking the rules reflects badly on my reputation with my peers*	Strongly disagree	Strongly agree	4.1	q3rep	Group +	4.02	0.76	0.76	**0.657**
	Group 3	*Getting a criminal record for carrying out illegal water activities is a strong deterrent*	Strongly agree	Strongly disagree	4.3	q3crim	Group +	3.65	0.66	0.66	
	Group 4	*Illegal water extraction occurs because of a desire for economic advantage*	Strongly disagree	Strongly agree	4.4	q3econ	Group -	3.39	0.60	0.40	

*see[26]

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NOTE: references 31 and 32 belong to Supplementary Methods