Water-controlled wealth of nations

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Population growth is in general constrained by food production, which in turn depends on the access to water resources. At a country level, some populations use more water than they control because of their ability to import food and the virtual water required for its production. Here, we investigate the dependence of demographic growth on available water resources for exporting and importing nations. By quantifying the carrying capacity of nations on the basis of calculations of the virtual water available through the food trade network, we point to the existence of a global water unbalance. We suggest that current export rates will not be maintained and consequently we question the long-term sustainability of the food trade system as a whole. Water-rich regions are likely to soon reduce the amount of virtual water they export, thus leaving import-dependent regions without enough water to sustain their populations. We also investigate the potential impact of possible scenarios that might mitigate these effects through (*i*) cooperative interactions among nations whereby water-rich countries maintain a tiny fraction of their food production available for export, (*ii*) changes in consumption patterns, and (*iii*) a positive feedback between demographic growth and technological innovations. We find that these strategies may indeed reduce the vulnerability of water-controlled societies.

Most of the water we use is to produce the food we eat. With the world's population that has doubled every 40 y there is a growing concern that water limitations will soon impede humanity to meet its food requirements (1–7). The urgency to deal with this alarming situation by developing durable socio-political and economic strategies that promote a sustainable use of the environment and its natural resources was at the core of the recent Rio+20 Earth Summit organized by the United Nations (7, 8). In recent years a number of studies have combined projections of population growth with predictions of water availability and agricultural productivity under a variety of climate change and land use scenarios. These predictions have been used to assess whether mankind will run out of water in the next few decades and to investigate possible strategies to deal with the global water and food crisis (9–15). At the regional scale, there are several areas of the world where the demand has already exceeded the supply of renewable freshwater resources (16–19). How can this negative water budget be sustained? It can be sustained mainly by importing food. The import of food commodities is associated with a virtual transfer of freshwater resources from production to consumption areas (20). Virtual water trade allows some populations to exceed the limits imposed by their local water resources (14, 21, 22). By sustaining demographic growth above the regional carrying capacity, virtual water trade has mitigated the effects of drought and famine in many regions of the world (14, 23). Thus, the redistribution of virtual water (VW) resources often appears as a remedy to regional water crises (22, 23). Even though, presently, most exporting countries can afford to sustain VW exports, their demographic growth might soon limit the amount of VW resources they can place on the global market. At some point these societies will have to decide whether they want to sustain the existing export rates or prefer to reduce the exports to meet their own food demand. What are the global implications of these two scenarios? To answer this question, we need to relate demographic growth both to the available freshwater resources and to global patterns of VW trade. We first investigate current trends of demographic growth and then develop model-based predictions of how the population is expected to change as water-rich countries start reducing their exports.

Carrying Capacity of Nations

We classify all countries around the world into five groups, depending on their supply and demand of VW and on the resulting balance or unbalance between available and consumed water resources (Fig. 1). We observe that the water-rich regions are in North and South America, Australia, and the former Soviet Union (or "Eastern Bloc"). These regions are known for being major VW exporters (24). Virtual water-dependent regions (i.e., regions that need VW imports to meet their demand) are mainly in Europe, Mexico, and the western side of South America. Despite VW trade, large parts of Africa and Asia remain affected by water stress. Because food production is the major form of freshwater consumption by human societies (25), we calculate the "carrying capacity" of a nation, i.e., its maximum sustainable population, on the basis of the water resources currently available for agriculture and livestock. The carrying capacity, although difficult to quantify, is a key notion for characterizing the relation existing between demographic dynamics and their possible resource limitation (7–9). Here we show that for almost one-third of all of the world's nations (i.e., water-rich and VW-dependent countries), the carrying capacity depends on their food availability, which, in turn, depends on the available water resources. Therefore, a quantitative estimate of the average local carrying capacity $\overline{K}^i_{loc}$ of country i is obtained by dividing the total water currently available for food production in that country [i.e., the current footprint of crops, grazing, and livestock (20, 21)] by the volume of water, W^i_c, used to produce the food consumed on average by one individual in that nation (16, 19, 20). $\overline{K}^i_{loc}$ is the maximum population sustainable with the available local freshwater resources of country i and is expressed in terms of the number of individuals (for all details see *SI Text*). The virtual carrying capacity $\overline{K}^j_V$ is the maximum sustainable population of country j when VW imports and exports are accounted for. Thus, the virtual carrying capacity depends on the structure of the global VW trade network (26). We also may incorporate in our modeling approach the impact on $\overline{K}$ of changes in consumption patterns, crop expansion, and increase in the efficiency of agricultural production (*SI Text*).

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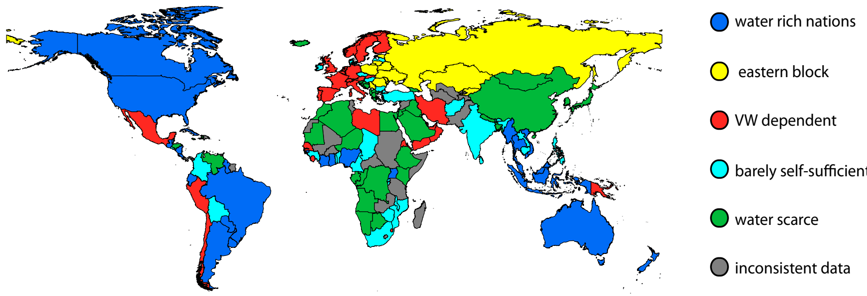

Fig. 1. Map of the world's countries classified on the basis of their dependency on local and virtual water resources, based on data for the 1996–2005 period (20, 21). Countries are water rich when their mean population, $\overline{x}$, is less than $0.8\overline{K}_{loc}$; virtual water dependent if $\overline{K}_V > \overline{x} > 1.20\overline{K}_{loc}$; barely self sufficient if $\overline{K}_{loc} \approx \overline{x}$ (i.e., $0.80\overline{K}_{loc} < x < 1.20\overline{K}_{loc}$); and water scarce if $\overline{x} > \overline{K}_V > \overline{K}_{loc}$. Countries for which the data exhibit inconsistencies (i.e., $\overline{x} > \overline{K}_{loc} > \overline{K}_V$) are shown in gray. A separate analysis has been carried out for the countries from the influence zone of the former Soviet Union (or the "Eastern Bloc") because in the past two decades their demographic dynamics have been affected by major political changes not related to freshwater resources (*SI Text*).

Demographic Growth and Water Availability

We analyze and model the relation between demographic growth and the water balance of water-rich and VW-dependent countries (for a total of $n = 52$ nations), using a stochastic logistic model. The population dynamics, $x^i(t)$, of nation i are expressed as (*SI Text*)

$$\frac{dx^i(t)}{dt} = \overline{\alpha}^i x^i(t)\left(1 - \frac{x^i(t)}{K^i}\right), \qquad [1]$$

where $i = 1, 2, \ldots, N$. K^i is treated as a random variable to account for stochastic fluctuations in available resources. We use this stochastic treatment because confidence intervals are not available for estimates of the water footprint of agricultural products used to calculate the carrying capacities (21). Thus, K^i is expressed as $K^i = \overline{K}^i + \xi$, ξ is a white Gaussian noise with mean $\langle \xi \rangle = 0$ and covariance $\langle \xi(t)\xi(s) \rangle = \sigma^2_{\overline{K}^i}\delta(t-s)$ (*SI Text*). $\langle \cdot \rangle$ denotes the average with respect to the stochastic fluctuations, whereas $\sigma^2_{\overline{K}^i}$ is the intensity of the fluctuations, and $\delta(.)$ is the Dirac delta function. The model is based on two key parameters: $\overline{\alpha}^i$ and $\overline{K}^i$. The mean population growth coefficient $\overline{\alpha}^i$ is determined for each nation, using demographic data for the period of record 1970–2010 (*SI Text*). To assess whether the demographic growth of a nation is driven by either local or virtual water availability, we consider both the case of population dynamics controlled by local water resources (i.e., with average carrying capacity, $\overline{K}^i = \overline{K}^i_{loc}$) and the effect of VW trade (i.e., $\overline{K}^i = \overline{K}^i_V$).

Fig. 2 summarizes the results of this analysis. We stress that the effective carrying capacities are obtained from direct evaluation of the actual virtual water availability and water footprint calculations (*SI Text*) and not from fit of demographic data. The

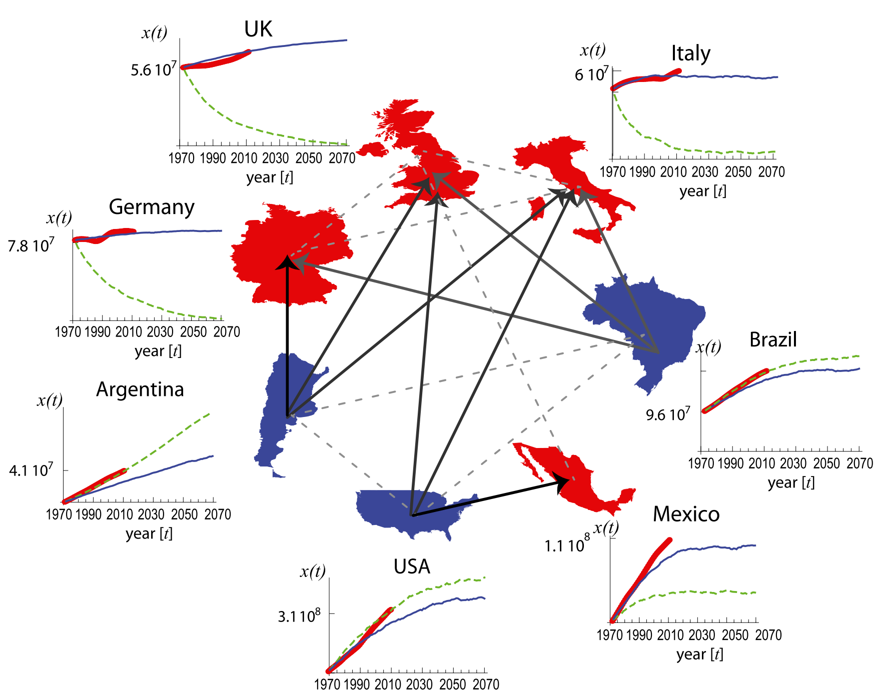

Fig. 2. Comparison between the logistic model given by Eq. **1** and demographic data (red dots) from 1970 to 2011 (*SI Text*) for three water-rich (blue) and four virtual water-dependent countries (red). These nations are connected through the VW trade web. The green dashed lines represent the numerical simulations of Eq. **1** with carrying capacity $K^i = K^i_{loc}$, whereas the blue lines correspond to the case of growth driven by the virtual carrying capacity $K^i = K^i_V$. Plots for the entire set of water-rich and trade-dependent countries can be found in *SI Text*. The evolution of water-rich nations agrees with Eq. **1** with $K^i = K^i_{loc}$, whereas for water-dependent countries the demographic growth is driven by Eq. **1** with $K^i = K^i_V$.

average demographic growth of water-rich countries is well described by the logistic model (Eq. **1**) with $K^i = \overline{K}^i_{loc}$, which indicates that the growth of these populations is driven by local water availability and is not limited by the important export of VW sustained by these nations. Interestingly, several nations seem to have just reached a critical phase in their demographic growth: the point of separation between the local water and the VW regime (*SI Text*). On the other hand, demographic growth of VW trade-dependent nations follows the logistic model with $K^i = \overline{K}^i_V$; thus, VW inputs may sustain the demographic growth of populations that increasingly rely on external VW resources (*SI Text*). In these countries population growth would not be sustainable without the import of VW from other regions. The fact that demographic growth in water-rich countries is independent of their VW exports, whereas water-poor nations increasingly rely on VW imports, highlights a situation that, in the long run, will be unbalanced and unsustainable. These results indicate that both water-rich and trade-dependent populations are growing to rely on the same pool of resources. At some point it will happen that, to meet their own demand, water-rich countries will have to reduce their exports, thereby causing the emergence of water limitations in trade-dependent countries. For instance, during the 2008 food crisis some exporting countries panicked and banned the exports of food crops (27). Unless new freshwater resources become available or investments for a more water-efficient agriculture are made, these populations will have to decrease.

Sustainability of Future Scenarios

To investigate these effects we use the logistic model (Eq. **1**) coupled with the dynamics of food trade through the VW network (Fig. 3*A*). We first build a bipartite network with N nodes that interconnects m water-rich nations (blue nodes $r = 1, 2, \ldots, m$) to VW trade-dependent countries (red nodes $p = 1, \ldots, N - m$). We investigate two scenarios. In the first one, the population in blue nodes grows following Eq. **1** with $\overline{K}^r = (1-\beta)\overline{K}^r_{loc}$, where β is the maximum fraction of $\overline{K}^r_{loc}$ that water-rich countries are willing to place in the long term ($t \to \infty$) in the global VW trade market. At any time t, a water-rich country, r, with population $x^r(t)$ shares with trade-dependent nations a volume of water equivalent to $\overline{K}^r_{loc} - x^r(t)$; we assume that this water is equally partitioned among all of the d_r trade-dependent countries connected to that blue node (i.e., d_r is the degree of node r). Therefore, the population $x^p(t)$ of a red node, p, grows according to Eq. **1** with virtual carrying capacity $\overline{K}^p_V = \overline{K}^p_{loc} + \sum_{r=1}^m a_{rp}(\overline{K}^r_{loc} - x^r(t))W^r_c/(W^p_c d_r)$, where a_{rp} is the adjacency matrix describing the virtual water trade network ($a_{rp} = 1$ if r and p are connected; $a_{rp} = 0$, otherwise). The case $\beta = 0$ corresponds to the purely competitive case, where in the long run $x^r(t) \to \overline{K}^r_{loc}$ and no water is exported because all resources are used to support the local population of the blue node r. The second scenario takes into account plausible crop expansions, increases in agricultural production efficiency, and changes in diet and consumption rates (19, 23) (*SI Text*), while the cooperation regime is turned off ($\beta = 0$). The relevant dynamics are expressed by the same equations as in the previous case, but critically endowed with time-dependent local carrying capacities, $\overline{K}_{loc}(t)$, and per capita virtual water consumption, $W_c(t)$. In particular, we impose a growth rate in the local resources [i.e., in $\overline{K}_{loc}(t)$] to account for possible cropland expansions and crop yield enhancement in existing croplands and a decrease in per capita virtual water consumption [i.e., in $W_c(t)$] due to new practices that reduce water loss (19) and changes in consumption patterns (28). We also consider the case in which a positive feedback exists between demographic growth and technological innovations (e.g., water reuse, rainwater harvesting, or new desalination methods) as suggested by von Foerster's Doomsday model of demographic growth (29). Within the context of the logistic growth presented here, von Foerster's arguments (29) imply that the carrying capacity increases from $\overline{K}_{loc}$ to $\overline{K}^{1/\nu}_{loc}$ (with $\nu < 1$).

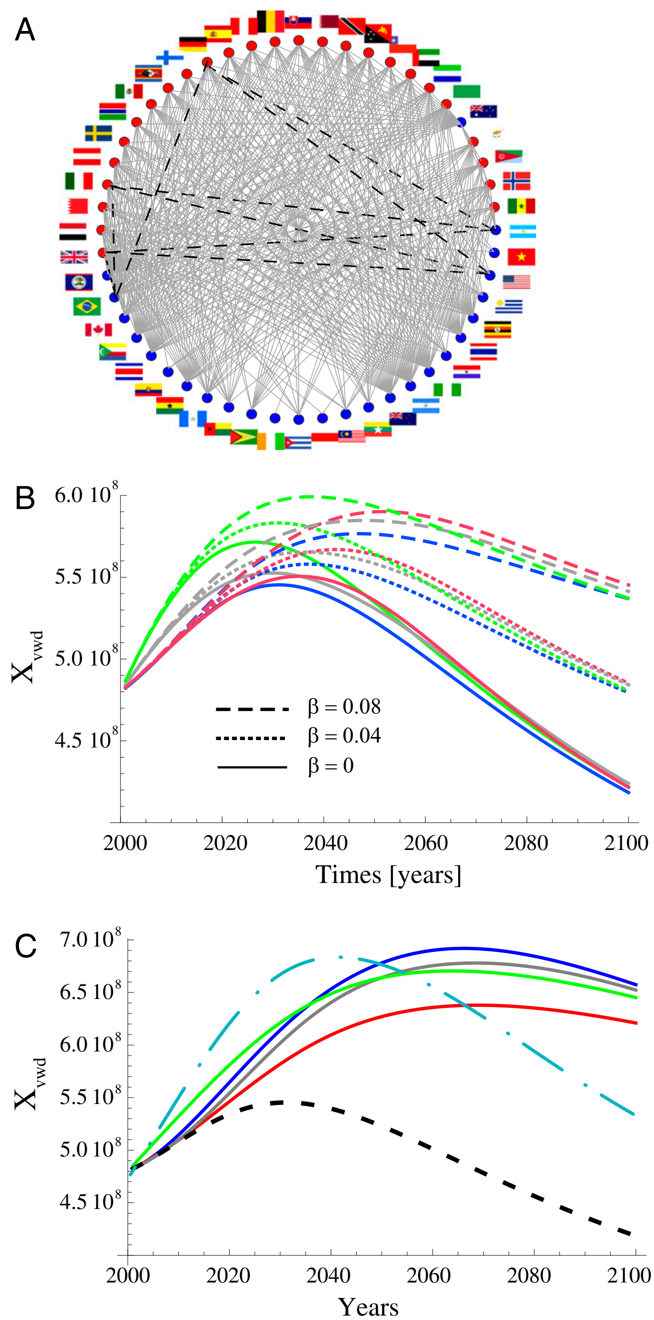

Fig. 3. (*A*) An example of a simulated virtual water network. Blue nodes represent water-rich nations, and red nodes are the VW trade-dependent countries. In *B* and *C* we investigate the logistic model of coupled population dynamics in four different types of network: random graph (blue lines), small world network (red lines), scale-free network (gray lines), and the graph with topological properties similar to those observed in the real global VW trade network (green). All details on the network construction can be found in *SI Text*. (*B*) Total population X_{vwd} of all VW-dependent nations as a function of time in the pure competitive case ($\beta = 0$, solid lines) and in two different cooperative regimes ($\beta = 0.04$, dotted lines; and $\beta = 0.08$, dashed lines). (*C*) Demographic dynamics of VW-dependent nations according to scenario 2 (but in the absence of cooperation, i.e., $\beta = 0$), which accounts for (*i*) an increase in productivity efficiency, crop expansion, and a decrease in consumption rates (solid lines) and (*ii*) a positive feedback between demographic growth and technological innovations (dashed-dotted line), where the local carrying capacity in Eq. **1** decreases from $\overline{K}_{loc}$ to $\overline{K}^{1/\nu}_{loc}$, with $\nu = 0.99$ (29). The black dashed line corresponds to scenario 1 for the existing virtual water trade network (26).

Discussion and Conclusions

To evaluate the impact of the network structure, we investigate the system's dynamics in the two above scenarios, using four types of networks with different structural properties but the same number of nodes and average number of links. For the first scenario, we find that in the purely competitive case ($\beta = 0$) the population of trade-dependent countries increases in the first 25 y and decreases in the subsequent years as a result of water limitations arising from the exclusion from the access to water resources controlled and claimed by water-rich countries (*SI Text* and ref. 30). This decline continues in the following decades as a result of demographic growth in water-rich populations (Fig. 3*B*). This behavior appears to be very robust and independent of the topological properties of the underlying network. If trade-dependent countries use more VW resources than they control, their population will strongly decrease once the water-rich countries start reclaiming all of the water resources they have access to, no matter how water is redistributed among the trade-dependent virtual water countries. The results are robust and do not qualitatively change with different strengths of the fluctuations of K in the range $0 < \sigma_K < 0.20\overline{K}$. Interestingly, this decrease in the trade-dependent population is reduced if a cooperative regime (i.e., $\beta > 0$) is considered. If water-rich countries keep a fraction, $\beta > 0$, of their water resources in the VW global market, VW-dependent countries can sustain a larger population, which increases as a function of β (Fig. 3*B*). The overall effect of a cooperative regime is a long-term increase in the total global population and thus a more sustainable demographic growth. In this cooperative regime, the network topology affects the coupled VW-demographic dynamics (*SI Text*). We finally note that the sensitivity of the demographic dynamics on β is very strong, and just a small departure of β from zero may lead to substantial reductions in the decrease of trade-dependent populations (Fig. 3*B* and *SI Text*). Similarly, strategies based on the enhancement of productivity efficiency and a decrease in per capita global consumption result in a remarkable relief for trade-dependent countries, whose populations are subjected to less pronounced declines (Fig. 3*C*). We also find that changes in consumption patterns and greater equity in per capita consumption would not be sufficient to meet the increasing demand of a growing human population. In fact, in the long run, if the growth rate of $\overline{K}_{loc}(t)$ tends to zero, the trade-dependent populations will peak and then inevitably decline (*SI Text*). On the basis of this analysis, in the absence of cooperation ($\beta = 0$) the decline in the trade-dependent population is expected to start around 2030, a date that is close to von Foerster's Doomsday date (29). On the other hand, in the presence of cooperation ($\beta > 0$) the decline is expected to occur between 2040 and 2060, depending on the intensity of the cooperative regime (Fig. 3*B*). We note that similar characteristic timescales have been discussed in ref. 31.

Despite the presence of a number of other environmental, cultural, and health-related factors not included in this study, this analysis points out how VW trade is only a temporary solution to a local-to-regional unbalance between populations and food production. The existence of this unbalanced condition might be mitigated if a cooperative regime among water-rich and VW-dependent nations continues to exist even once the excess of VW in the exporting countries is strongly reduced by their demographic growth ($\beta > 0$). We finally show that strategies aiming at an increase in productivity efficiency through agricultural practices that enhance crop yields while reducing water losses (e.g., water harvesting, water conservation, genetically modified crops) or increased water use efficiency resulting from increased atmospheric CO_2 concentrations improve the sustainability of trade-dependent societies with respect to a decrease in export rates from water-rich countries.

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