nature climate change

PERSPECTIVE

PUBLISHED ONLINE: 25 JUNE 2013 | DOI: 10.1038/NCLIMATE1789

Integrated analysis of climate change, land-use, energy and water strategies

Mark Howells[1*], Sebastian Hermann[1*], Manuel Welsch[1], Morgan Bazilian[1], Rebecka Segerström[1], Thomas Alfstad[2], Dolf Gielen[3], Holger Rogner[4], Guenther Fischer[4], Harrij van Velthuizen[4], David Wiberg[4], Charles Young[5], R. Alexander Roehrl[6], Alexander Mueller[7], Pasquale Steduto[7] and Indoomatee Ramma[8]

Land, energy and water are our most precious resources, but the manner and extent to which they are exploited contributes to climate change. Meanwhile, the systems that provide these resources are themselves highly vulnerable to changes in climate. Efficient resource management is therefore of great importance, both for mitigation and for adaptation purposes. We postulate that the lack of integration in resource assessments and policy-making leads to inconsistent strategies and inefficient use of resources. We present CLEWs (climate, land-use, energy and water strategies), a new paradigm for resource assessments that we believe can help to remedy some of these shortcomings.

Following the 2007–2008 and 2011 food price crises, renewed concerns over food security have surfaced, in both middle- and high-income regions. In response, the commercial pressures on land are increasing globally[1,2]. Meanwhile access to water is a concern, with an ever-increasing number of people affected by water shortages[3]. Energy demand is projected to grow by one-third by 2035, and the prospects for achieving this growth while keeping global temperature increases below 2 °C are looking progressively slimmer[4]. This suggests that efficient management and use of these resources will be of utmost importance in the coming decades.

At the same time these resources are an integral part of the development challenge. Close to one billion people are undernourished and another billion are malnourished. At present 1.2 billion people live in areas where there is physical water shortage, a number that is expected to grow in coming decades[3]. A further 1.6 billion people suffer from economic water shortages, where the infrastructure to deliver clean water is not in place. Energy access is also far from universal, with 1.3 billion people living without access to electricity[4] and 2.7 billion with no access to modern and healthy forms of cooking.

A key element in management of the land, water and energy systems is that they are inextricably linked. Agriculture alone accounts for 70% of global water withdrawals and industry for another 22%, most of which is for cooling thermal processes in power generation and manufacturing[5]. Land is used to grow feedstocks for biofuels production, and over the 2008–2018 period biofuel may account for about half of the global increase in demand for maize and wheat and a third of the increase in demand for oil seeds[6]. By 2030 the area of land devoted to biofuel feedstock is estimated to be 37 million hectares (ref. 7). Water delivery, transportation and treatment are consumers of energy, and the expanding practice of water desalination is highly energy-intensive. Energy is also needed to produce fertilizer and to prepare land, harvest crops, and dry and process agricultural produce.

Current assessment practices

The information above points to a need for systematic national-level integrated assessments, but this is not standard practice. Integrated environmental assessments are not uncommon, and the practice of project-level assessment is now almost universal and mandatory in most countries and sectors[8], but they typically occur at a level of detail that is of limited use for policymakers at the national level. National assessments of land-use, energy and water are often carried out in isolation by separate and disconnected institutional entities. An institution whose main responsibility lies in the management of water resources is likely to treat food and energy systems mainly as end users[9]. A food and agriculture assessment might see energy and water as inputs[10–12], whereas energy assessments are likely to treat biomass and water as resources. (Many energy assessments fail to consider water at all.) A stylized summary of current assessment practices can be found in Table 1.

Although the lack of integrated assessments at the national level has been noted in recent literature[13], increasingly more inclusive approaches are being developed (for example bio-energy[14], diet[15], water[16] and land[17]). A comprehensive review of integrated assessments is provided by Pollit *et al.*[18]. That work notes both the strides made and the potential for further development of integrated assessment models. Integrated assessments have tended to tackle regional and global questions, often related to trans-boundary pollution. Owing to the volume of analysis, these have been designed in a focused and disciplinarily idiosyncratic manner. As the respective fields are moving, advancements encourage exclusive strategically selective focus or wholesale reworking of individual assessment methods, which in turn need to be reintegrated. The International Atomic Energy Agency (IAEA)[19] suggests developing stylized general approaches to various integrated assessments that focus at the national level, integrated existing knowledge and approaches.

[1]KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden. [2]International Atomic Energy Agency, Vienna International Centre, PO Box 100, A-1400 Vienna, Austria. [3]International Renewable Energy Agency, IRENA Innovation Technology Centre, Robert-Schuman-Platz 3, 53175 Bonn, Germany. [4]International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria. [5]Stockholm Environment Institute, 1 Curtis Avenue, Somerville, Massachusetts 02144, USA. [6]United Nations Department of Economic and Social Affairs, 405 East 42nd Street, New York 10017, USA. [7]Food and Agriculture Organization, Viale delle Terme di Caracalla, 00153 Rome, Italy. [8]Agricultural Research and Extension Unit, 3rd Newry Complex, St Jean Quatre, Bornes, Mauritius. *e-mail: mark.howells@energy.kth.se; sebastian.hermann@energy.kth.se

Table 1 | Stylized review of integrated assessment practices.

	Subnational	National	Regional and global
Project	EIA, ESIA, almost universal and mandatory		Ad hoc IA of cross-border projects
Programme	Isolated examples	SEA mandatory in Europe and selected other countries; CADO in selected developing countries	EIA and PIA by UN, development banks and global funds
Policy			IA by OECD, UNEP, G20
Sector	Conventional sectoral planning	Conventional energy and infrastructure planning	Many energy, land-use and water models
Multisector	Significant number of academic applications	Few examples. CLEWS	Moderate number of IAs

The darker the shading, the more commonly used across the world. CADO, comparative assessment of development options; CBA, cost–benefit analysis; EIA, environmental impact assessment; ESIA, environmental and social impact analysis; HIA, health impact assessment; IA, integrated assessment; PIA, poverty impact assessment; SEA, strategic environmental assessment; SIA, social impact analysis. Based on UNESCAP[54] and OECD[55].

The implication is that important interactions between the resource systems might be missed that could have unintended consequences. This could lead to incoherent policy-making, where a strategy or policy implemented in one area undermines a policy goal in another. For instance, the strong drive by many governments to promote biofuels over the past decade did not foresee the full impact of rapid biofuel expansion on land and food markets, nor the potentially adverse consequences of land-use change associated with the expansion of biofuel production on the emissions of greenhouse gases (GHGs)[20,21]. The latter effect directly counteracted one of the main objectives of the policy. A more integrated assessment across resource systems might have alerted policymakers to these pitfalls and led to policies that had better safeguards. Conversely, there might be considerable co-benefits across systems for certain plans or policies. An integrated assessment method that can capture the vulnerability of the agricultural, water supply and energy sectors to changes in rainfall patterns is better positioned to assess the robustness of a given policy or strategy. It is therefore possible to study potential conflicts or co-benefits not only with respect to the management of the three resource systems but also between climate change mitigation and adaptation.

The road to and from Rio

The Agenda 21 action plan for sustainable development was adopted by more than 178 governments at the United Nations Conference on Environment and Development (UNCED)[22], in Rio de Janeiro in 1992. It outlined actions to be taken by governments and UN organizations as well as civil society. Later that year, the United Nations Commission on Sustainable Development (UNCSD) was created to ensure effective follow-up of UNCED, and to monitor and report on implementation of the agreements at the local, national, regional and international levels.

Agenda 21 highlighted the need for integrated assessment, and later work has supported the idea that current practices are not sufficient to support the decision-making process and help to ensure sustainable development and future access to food, water and energy[23–25]. To address this, the need for an integrated framework to assess climate, land-use, energy and water strategies (CLEWs) emerged from side events dedicated to this topic at recent UNCSDs. Of the most recent work, that introduced by the government of Mauritius[26] is highlighted in the case study reported below. The CLEWs framework featured in several events at Rio+20 (refs 27–29). At that meeting, the Mauritian government went further and declared[30] to the general debate that its '… government program for 2012–2015 provides for the appointment of a high-level CLEWs panel which will ensure an integrated approach to all policies related to Climate, Land-use, Energy and Water strategies' based in part on findings and utility of work that we now describe.

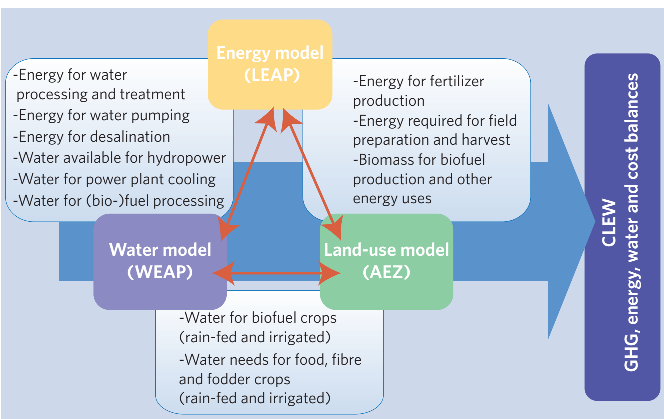

Figure 1 | The CLEWS framework. The framework integrates LEAP (Long-range Energy Alternatives Planning tool by SEI), WEAP (Water Evaluation and Planning tool by SEI) and AEZ (Agro-Ecological Zoning by IIASA and FAO) models with climate change scenarios.

The CLEWS framework

The idea behind the CLEWS framework is simple: land, energy and water resource systems are highly integrated, and any assessment of these resources should ideally treat them as such. Rather than developing a new fully integrated analysis tool we draw on existing well-tested assessment methodologies for each of the three resources and integrate aspects of these. A module-based approach is adopted, where data are passed between sectoral models in an iterative fashion. A key to this approach is to identify the points at which the resource systems interact and to establish appropriate data exchanges between the modules (that is, water requirements in the land-use and energy systems; energy needs for water supply and land-use; and land requirements for energy and water infrastructure). We then introduce a process where data for these intersection points are exchanged between modules. The output from one module forms the input for the two others, which then are solved sequentially and each pass data back to the two other models. This process is repeated through a series of iterations until a convergent solution is found. An example of a CLEWS schematic is shown in Fig. 1.

The water and land-use models are calibrated using future expectations of rainfall and other parameters, which can be based on outputs from climate models. This allows the simultaneous exploration of the relationships and interdependencies of these resource systems, and the trade-offs and co-benefits between mitigation and adaptation strategies.

An advantage of relying on previously established modelling methodologies is that the cost in effort and resources of introducing the framework is lower than if one were to build a fully integrated model from scratch. Furthermore, it makes it easy to bring together

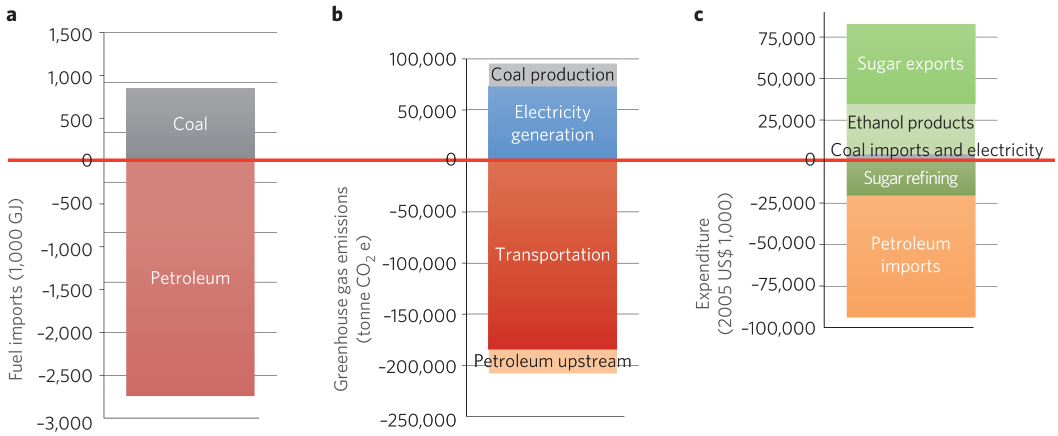

Figure 2 | The impact of transforming two sugar-processing plants to produce second-generation ethanol in Mauritius (projections for 2030). **a**, Fuel imports compared with the baseline (in 1,000 GJ). The import dependence decreases. Imports of petroleum are reduced as ethanol replaces it as a motor fuel. Some bagasse (a sugarcane by-product) is diverted from electricity generation to ethanol production. This needs to be compensated for by increased imports of coal. **b**, GHG emissions compared with the baseline (in tonnes of CO_2 equivalent; CO_2e). Total GHG emissions are reduced. Tailpipe and upstream emissions are reduced as petroleum is replaced by ethanol. The increased use of fossil fuels (in place of bagasse) for electricity generation results in lower overall emissions. **c**, Estimated expenditure compared with baseline (in 2005 US$1,000). Ethanol production has economic consequences. As some of the sugar is converted to ethanol, the expenditures for sugar refining and petroleum imports are reduced. This outweighs the reduced earnings from sugar export and the costs associated with ethanol production and the increase in coal imports.

experts from the various disciplines to work together. Departments, ministries or institutions can participate in collaborative work, with each participant contributing with their already established tools and expertise. This greatly reduces learning curves and allows for better use of already acquired knowledge and experience. An extra benefit of modularity is that the individual components can still be run individually. This means that any improvements or updates made to them during the course of a CLEWS study can still be applied when the models are run separately. Furthermore, it allows users to check the impact of the integration by comparing model behaviour in integrated mode against stand-alone mode.

Flows of energy, water and agricultural products may well cross the study boundary, leading to potential feedback outside this boundary. Changes in import or export of agricultural commodities, for instance, might lead to changes in the prices of those commodities, inducing changes in production elsewhere. If the area of study or the change in resource flow is small compared with the overall size of the market, these feedback effects might be negligible. But if they are not, there may be a need to develop parallel models that are broader in geographical scope, or to adopt a simpler representation through elasticities of demand and supply based on available literature.

Although we suggest that this work provides a step forward for practical integrated systematic analysis, many issues remain unaddressed. Without quantification and valuation of ecosystem services it is difficult to assess, for example, the impact of cropping practice on loss of biodiversity. The expansion of agriculture into natural habitats and the adoption of monoculture, along with other management practices, have had a detrimental impact on biodiversity[31]. Loss of biodiversity may have severe long-term effects on a wide range of natural ecosystem services, which in turn have effects on freshwater resources, soil health, and climate variability and change. As Rockström *et al.*[32] state, "We can say with some confidence that Earth cannot sustain the current rate of loss without significant erosion of ecosystem resilience." Biodiversity considerations were not part of the research carried out so far. This and other important interwoven systems and resources will, however, provide useful challenges to tackle as the art of assessments is taken forward.

CLEWS in Mauritius

The Republic of Mauritius is a small island nation in the Indian Ocean, with a population of 1.3 million people. It covers an area of 1,865 km^2 and is situated in the tropical climate zone. The country has achieved rapid growth and economic diversification over recent decades and is now an upper-middle-income nation. We selected Mauritius as our first CLEWS case study because the island is facing decreasing water availability and is vulnerable to climate change. The agricultural sector contributes significantly to the country's export earnings through sugar sales to Europe. Furthermore, it is a priority for the country to reduce its dependence on energy imports, and at the same time the government has stated its aim to reduce anthropogenic greenhouse gas emissions.

Sugarcane plantations cover 80–90% of cultivated land on the island. The sugar business has been an important contributor to the economy and a key source of export and foreign exchange earnings. Mauritian sugar exporters have, however, recently lost the preferential access to the EU market they used to enjoy under the ACP sugar protocol. The protocol gave them fixed quotas at guaranteed internal (subsidized) prices. This arrangement has ended, and Mauritian producers are now exposed to a more competitive and volatile market.

The question has therefore been raised of whether it would be in the national interest to promote a local biofuel industry. This implies diverting sugar cane produced on the island away from export markets towards domestic processing into ethanol for sale as a motor fuel. The country would concede losses in export earnings from sugar trade in order to reduce the reliance on petroleum fuel imports. Reduced imports of petroleum would improve energy independence and reduce petroleum import costs as well as GHG emissions. Whether or not this strategy is favourable depends on the cost of domestic sugar ethanol production, general income and socio-economic benefits, the price spread between petroleum and sugar, and the value placed on energy security and GHG emission reductions—as well as unintended and unforeseen secondary impacts.

To asses this policy with a CLEWS approach, an analytical framework based on the Agro-Ecological-Zoning (AEZ) land-use[33], LEAP energy and WEAP water modelling tools was developed with

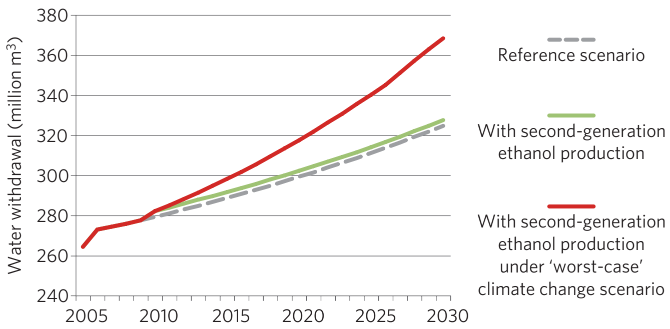

Figure 3 | Changes in overall water withdrawals for selected integrated CLEW scenarios in Mauritius. Water withdrawals increase under different climate change scenarios. To compensate for reduced rainfall, irrigation will have to be expanded to previously rain-fed sugar plantations and farms. This could lead to higher withdrawals of surface and groundwater.

local analysts. The models were calibrated using the recent data and various scenario assumptions and subsequently linked (more detail is available in the Supplementary Information).

An integrated 'baseline' scenario consistent with national plans was developed to act as a reference point for the scenario-based analysis. This reference case assumes that Mauritian sugar exporters gradually lose market share to lower-cost producers but are able to find sufficient markets to maintain current production levels. Sugar cane thus remains the dominant crop grown on the island and sugar the mainstay of export agriculture. Water supply relies mainly on withdrawals of surface water and groundwater, with groundwater extraction being limited by concerns over potential saline intrusion into aquifers if they are depleted. If demand exceeds the supply of surface and groundwater, the shortfall will have to be met by desalination of sea water. Some resorts and hotels have already adopted this strategy and invested in small-scale water desalination facilities. This displaces water withdrawals from rain-fed basins, freeing it up for use elsewhere, such as irrigation. For the baseline scenario, the national investment plan for the power sector was adopted, envisaging continued reliance on coal-fired generation to meet future growth in demand. This is estimated to be the lowest-cost supply option for Mauritius[34]. Investment in renewable electricity generation has so far been limited by concerns over costs and the integration of intermittent power supply into a grid with few dispatchable assets (generation resources whose output can be adjusted on demand). Weather patterns were assumed to follow recent trends.

In the first set of scenarios, the integrated effects of a strategy to begin production of bioethanol from sugar were evaluated. Given the history of sugar production in Mauritius and the fact that sugar-based ethanol is typically the lowest-cost biofuel, no alternative biofuel feedstock was considered in the scenario analysis. The introduction of bioethanol production involved the conversion of two major sugar mills to ethanol plants, and consequently diverting around 20% of the sugar cane to fuel production.

Some key results from the analysis are shown in Fig. 2. At the assumed prices (US\$80 per barrel (bbl) crude and US\$420 per tonne sugar), the reduction in petroleum import bills exceeds the revenue losses from sugar exports. Price developments in either market are uncertain and likely to be volatile, so this benefit is by no means guaranteed (for a petroleum price of US\$100 per bbl the sugar price would have to exceed US\$700 per tonne for the switch to ethanol to become unprofitable; in recent history petroleum prices have been higher and sugar prices lower). In times when the spread of sugar and petroleum prices is unfavourable to ethanol conversion, however, producers can return to selling raw sugar until relative price movements make ethanol production viable again, provided that investments have been made in flexible plants capable of this switch. Consequently, the decision to develop ethanol production capacity does not lock producers out of the sugar market during times when sugar prices are high.

In recent years, lower rainfall has led to water shortages on the island. The government has responded with policies to conserve water and introduce water desalination. If the reductions in precipitation continue in the longer term, the benefits and viability of the biofuel policy could be at risk. To explore this possibility, four general circulation models (GCMs: HadCM3, ref. 35; ECHAM4, ref. 36; CSIRO, refs 37,38; and CGCM2, ref. 39) that produce the necessary output to undertake AEZ[29] and WEAP analysis were used to calibrate rainfall pattern changes for all IPCC scenarios (A1 to B2)[40]. Noting that nine out of the ten predictions indicate a decrease in rainfall for Mauritius, a 'worst-case' scenario was developed based on the largest average monthly drop in rainfall. The adjusted rainfall patterns were used as model input to test how the policy performed under these conditions. The results are shown in Figs 3 and 4.

With lower rainfall, more water needs to be supplied through irrigation to maintain sugar cane production. This leads to higher withdrawals of water from rivers, dams and aquifers. The increased withdrawals of less plentiful surface water leads to a gradual drawdown of storage levels in reservoirs (Fig. 4).

The increase in water withdrawals also leads to higher demand for energy to drive pumps to bring the water from its source to the fields and to power water desalination plants. A positive feedback loop means that this leads to increased demand for cooling of thermal power plants and thus additional withdrawals of water (unless they are cooled by sea water). If the increase in electricity demand is met with coal-fired power generation as planned, then the GHG benefits of the ethanol policy are eroded by increased emissions from the power sector. Higher coal imports also have a negative impact on energy security. The benefits of this policy—which aimed to reduce energy import costs and emissions—are thus clearly vulnerable to the impacts of climate change, and the long-term viability of this strategy would be at risk if rainfall were to decrease further and droughts continue. In this event, producers would either have to scale back production or resort to expensive water desalination. Both of these options negatively affect the expected climate and energy security benefits of the policy, and both would be detrimental to the sugar and ethanol industry.

The water-constrained scenario does, however, also lead to better prospects for renewable electricity generation. Wind and photovoltaic electricity generation is typically much less water-intensive than fossil fuel generation. Furthermore, if power consumption for water desalination facilities makes up a significant share of total system load, intermittent resources such as wind could be integrated more easily. Because water storage is cheap and easy, it is not important that it is produced at a specific time. It could therefore be treated as an interruptible load and shut down in the event that wind generation is unavailable during times of high system load.

Lessons learned

Four key insights were gained through this work. The first is that this type of integrated assessment is imminently achievable, thanks to the availability of highly adaptable and configurable tools. A wide range of tools are available that could be used for CLEWS assessments, and users should be able to adopt a set of tools that are appropriate for their requirements. Second, although achievable, the process of integrating individual tools into a module-based framework requires considerable effort to ensure compatibility and efficient data transfer. A third insight is that fully integrated assessments may not always be fully compatible with the expediency that is sometimes required in policy analysis. The time required to develop and integrate the framework does not allow fast turnaround projects. Even when the framework is already set up, the iteration

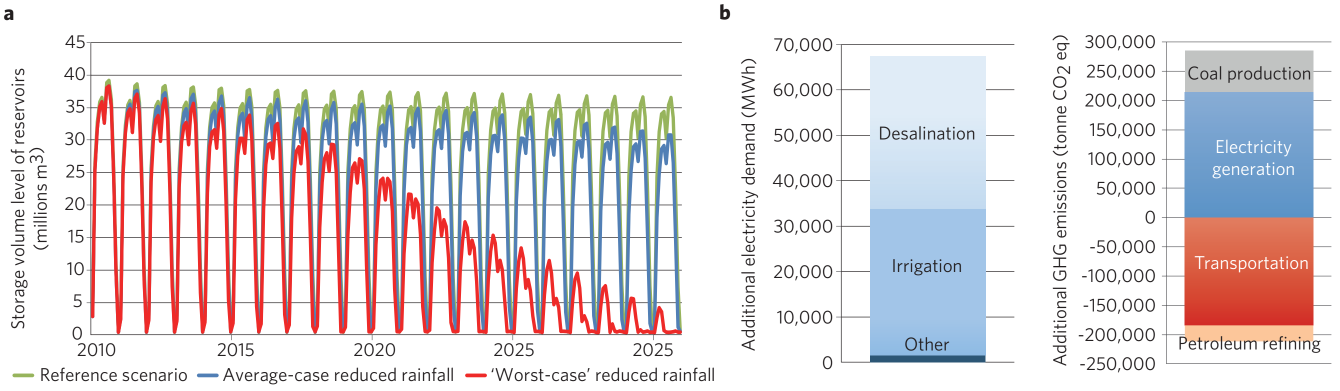

Figure 4 | Predicted impact of climate change on water availability in Mauritius, water-related energy consumption and GHG emissions (predictions for 2030). a, Storage volume levels in reservoirs in Mauritius under three climate change scenarios (in million cubic metres). **b**, Under the 'worst-case' climate change scenario, there is an extra electricity demand for water (compared with scenario without climate change impacts). This is mainly due to greater desalination requirements and the need for irrigation in sugar-cane plantations. **c**, The extra energy demand in this scenario leads to an increase in GHG emissions (compared with scenario without climate change impacts). This demand is largely met by coal-based electricity generation; the resulting emissions outweigh the emission benefits of the second-generation ethanol production.

process itself as well as the time required to check the results for errors and inconsistencies may be too long to fit into the policy-making process. Finally, acknowledging the integrated nature of these systems opens up a wide array of policy and strategic issues and concerns (which otherwise may not be easily revealed) that can be assessed through the lens of a CLEWs framework. It is possible to identify and study conflicting objectives and trade-offs, as well as synergies and co-benefits. The concept allows for the assessment of these aspects, not just across resource systems but also across mitigation and adaptation strategies.

Note that the scenarios are purely explorative. The framework allows for consistent physical flow, commodity and cost accounting, based on current knowledge as well as mass and thermodynamic balances. With these we can trace the implications of various assumptions to consistent future states — all of which are subject to much uncertainty. (In the case of Mauritius, sugar and petroleum prices, as well as the accuracy of climate models and their downscaling[41], for example, are highly uncertain.) Precisely for this reason, a transparent and flexible integrated framework can add value. It allows the analyst to test arrays of scenarios and relationships in a consistent and quantified manner, to help understand potential policy implications.

Next steps

Apart from ongoing input to the CSD process, the policy recommendations arising from the CLEWS case studies are being featured in the UN flagship publication for Rio+20, entitled "Sustainable Development in the 21st Century"[42], and a new case study for Burkina Faso is being finalized. UN agency technical assistance for governments on CLEWs is currently in the planning stage.

The International Renewable Energy Agency (IRENA) considers the water–energy–food nexus as an important topic and has developed a programme to assess CLEWs in Pacific Island states. Here, special emphasis will be given to the role of renewable energy in supplying daily needs at an affordable cost while maintaining sustainable development. The CLEWS framework is the subject of a Coordinated Research Project (CRP) under way at the IAEA. This project brings together researchers, scientists and analysts from member states. The CRP fills the dual role of providing an enabling environment for further development, adaption and application of the CLEWS framework as well as training practitioners in member states. The FAO has numerous related activities, with agriculture playing a central role (see for example refs 43–49). With a wide array of tools developed (see for example refs 50–53), efforts are under way to help facilitate further integrated analysis. A postgraduate research programme has been initiated at the Royal Institute of Technology, Sweden (KTH), based on related programmes and tools from various UN partners, the Stockholm Environment Institute and the International Institute for Applied Systems Analysis (IIASA). The initial aim is to help to develop this integrated framework, building on tools and methods developed by the aforementioned partners and others for policy-orientated research.

An increasing number of Governments and organizations are interested in applying the CLEWS concept as part of their assessment practices. To make CLEWS widely accessible and useful, especially to developing countries, effective partnerships between governments, academia and relevant organizations are needed.

Received 8 February 2012; accepted 26 November 2012; published online 25 June 2013.

References

1. Deininger, K. & Byerlee, D. *Rising Global Interest in Farmland: Can it Yield Sustainable and Equitable Benefits?* (World Bank, 2011).
2. Taylor, M. & Bending, T. *Increasing Commercial Pressure on Land: Building A Coordinated Response* (International Land Coalition, 2009).
3. Molden, D. (ed.) *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture* (Earthscan/IWMI, 2007).
4. International Energy Agency *World Energy Outlook* (IEA/OECD, 2011).
5. *Water for People, Water for Life* (UNESCO-WWAP/Berghahn, 2003).
6. *Agricultural Outlook* (OECD/ FAO, 2010).
7. *Biofuels and Food Security* IIASA Land Use Change and Agriculture Program Study (IIASA/OFID, 2009).
8. Wood, C. *Environmental Impact Assessment: A Comparative Review* 2nd edn (Prentice Hall, 2002).
9. Hellegers, P. *et al.* Interactions between water, energy, food and environment: Evolving perspectives and policy issues. *Water Policy* **10,** 1–10 (2008).
10. *World Economic and Social Survey: The Great Green Technological Transformation* (UNDESA, 2011).
11. Khan, S. & Hanjra, M. A. Footprints of water and energy inputs in food production. *Food Policy* **34,** 130–140 (2009).
12. Mushtaq, S. *et al.* Energy and water tradeoffs in enhancing food security: A selective international assessment. *Energy Policy* **37,** 3635–3644 (2009).
13. Rothausen, S. G. S. A. & Conway, D. Greenhouse-gas emissions from energy use in the water sector. *Nature Clim. Change* **1,** 220–223 (2011).
14. Van Vuuren, D. P. *et al.* Future bio-energy potential under various natural constraints. *Energy Policy* **37,** 4220–4230 (2009).
15. Stehfest, E. *et al.* Climate benefits of changing diet. *Climatic Change* **95,** 83–102 (2009).
16. Rothausen, S. & Conway, D. Greenhouse gas emissions from energy use in the water sector. *Nature Clim. Change* **1,** 210–219 (2011).
17. Letourneau, A. *et al.* A land-use systems approach to represent land-use dynamics at continental and global scales. *Environ. Model. Software* **33,** 61–79 (2012).

18. Pollitt, H. *et al. A Scoping Study on the Macroeconomic View of Sustainability* (Cambridge Econometrics/Sustainable Europe Research Institute, 2010); available via http://go.nature.com/Akj7HA
19. *Nuclear Technology Review 2009* Annex VI (IAEA, 2009); available at http://www.iaea.org/Publications/Reports/ntr2009.pdf
20. Searchinger, T. *et al.* Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **319,** 1238–1240 (2008).
21. Fargione, J. *et al.* Land clearing and the biofuel carbon debt. *Science* **319,** 1235–1238 (2008).
22. *Agenda 21: Earth Summit. The United Nations Programme of Action from Rio* (UN, 1993); available via http://go.nature.com/mpEyIM
23. Ayensu, E. *et al.* International ecosystem assessment. *Science* **22,** 685–686 (1999).
24. Fiksel, J. Sustainability and resilience: Toward a systems approach. *Sust. Sci. Practice Policy* **2,** 14–21 (2006).
25. Bazilian, M. *et al.* Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* **39,** 7896–7906 (2011).
26. *Statement by Ambassador Milan J. N. Meetarbhan* (Permanent Missions of the Republic of Mauritius to the UN, 2011); available via http://go.nature.com/3BFwNJ
27. *SIWI in Rio. Water Food and Energy Nexus: A Fundament for Green Economy* (Stockholm International Water Institute. Available at http://www.siwi.org/news/siwi-in-rio
28. *Sustainable Energy, Food, Water & Oceans* (UN, 2012); available via http://go.nature.com/q6h13e
29. Launch of *Sustainable Development for the 21st Century* report. Available via http://go.nature.com/M2JxJj (UNDESA, 2012).
30. *Address by His Excellency Devanand Virahsawmy, Minister of Environment and Sustainable Development of Mauritius* (UN, 2012); available via http://go.nature.com/y3wdkB
31. *The State of the World's Plant Genetic Resources for Food and Agriculture* (FAO, 1997).
32. Rockström, J. *et al.* A safe operating space for humanity. *Nature* **461,** 472–475 (2009).
33. *Global Agro-ecological Zones* GAEZ v3.0 (IIASA/ FAO, 2012); available via http://go.nature.com/1AZY9k
34. *Long-Term Energy Strategy 2009–2025* (Government of Mauritius, 2009).
35. http://go.nature.com/vXHLsV
36. http://www.mpimet.mpg.de/en/science/models/echam.html
37. http://www.csiro.au/
38. http://www.ipcc-data.org/is92/csiromk2_info.html
39. http://go.nature.com/7QEUP4
40. IPCC *Special Report on Emissions Scenarios* (eds Nakicenovic, N. & Swart, R.) (Cambridge Univ. Press, 2000); available at http://www.ipcc.ch/ipccreports/sres/emission/index.htm
41. Evans, J. CORDEX — An international climate downscaling initiative. *Proc. 19th Intl Congr. Modelling and Simulation* (2011); available via http://go.nature.com/vmizwT
42. *Sustainable Development in the 21st Century* (UNDESA , 2012); available via http://go.nature.com/XhDL1q
43. Aziz, E. *et al. Global Action on Climate Change in Agriculture: Linkages to Food Security, Markets and Trade Policies in Developing Countries* (FAO, 2011) available via http://go.nature.com/zqVX53
44. *Climate-Smart Agriculture. Managing Ecosystems for Sustainable Livelihood* (FAO, 2012); available via http://go.nature.com/p5r7Eh
45. Turral, H. *et al. Climate Change, Water and Food Security*. FAO Water Report No. 36 (FAO, 2011); available via http://go.nature.com/FSSnjq
46. *Save and Grow. A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production* (FAO, 2011); available at http://www.fao.org/ag/save-and-grow/index_en.html
47. *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW). Managing Systems at Risk* (FAO/Earthscan, 2011); available at http://www.fao.org/nr/solaw/the-book/en/
48. *Biodiversity for Food and Agriculture. Contributing to Food Security and Sustainability in a Changing World* (Platform for Agrobiodiversity Research, FAO, 2011); available via http://go.nature.com/CCFP8e
49. *Bioenergy and Food Security. The BEFS Analytica Framework* Environmental and Natural Resources Management Working Paper No. 16 (FAO, 2010); available via http://go.nature.com/clTrUq
50. FAO *Global Agro-Ecological Zoning*; available at http://gaez.fao.org/Main.html
51. *FAO Modelling System for Agricultural Impacts of Climate Change (MOSAICC)*; available at http://www.fao.org/climatechange/mosaicc/en/
52. *FAO's Framework Programme on Climate Change Adaptation (FAO-Adapt)*; available at http://www.fao.org/climatechange/fao-adapt/en/
53. *AquaCrop. The FAO crop-model to simulate yield response to water*; available at http://www.fao.org/nr/water/aquacrop.html
54. *Integrated Policy and Assessment in Sustainable Transport Development* (UNESCAP, 2006); available via http://go.nature.com/MfN7rd
55. *Good Practice Guidance on Applying Strategic Environmental Assessment (SEA) in Development Cooperation* (OECD, 2006).

Acknowledgements
We thank D. le Blanc (UNDESA) for insight and encouragement in problems that fall outside the scope of traditional planning approaches, and for his input to discussions and fora; Ø. Vessia (EC) for work on precursor efforts to this work; M. Radka (UNEP); L. Langlois (independent consultant); and O. Broad (KTH). The views and perspectives expressed in this article are those of the authors and do not necessarily reflect the views of the UN, associated UN Agencies or their senior management.

Author contributions
The experiments were conceived and designed by M.H., S.H. and H.R. The entire endeavour was overseen by M.H. The modelling experiments themselves (focusing on integration) were undertaken by M.H., M.W., S.H., C.Y. and G.F. Data analysis, and meta-data creation, were undertaken by S.H., M.W., T.A., C.Y. and G.F. Material and analysis tools were provided by C.Y. who developed the Mauritius WEAP model with S.H. M.W. developed the Mauritius LEAP model. G.F., H.V. and D.W. developed and advanced the AEZ model generally and specifically applied it to the case of Mauritius. A.M. and P.S. provided methodologies that were used to analyse crop–water–land interrelations. I.R. collected great volumes of base data needed to calibrate the models. R.R. provided an analysis of the tools and gaps in the integrated assessment space. M.H., H.R., T.A., D.G., M.B., R.R., P.S. and R.S. drafted sections of the paper.

Additional information
Supplementary Information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.H. and S.H.