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# Water: the invisible problem

Access to fresh water is considered to be a universal and free human right, but dwindling resources and a burgeoning population are increasing its economic value

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Water is an integral part of our daily lives and not just for drinking: when we wake up, we might take a shower, or sip coffee or tea; during the day we quench our thirst with all types of beverages; some of us water our gardens; we wash the laundry and the dishes; and by the end of the day, the average person in a Western society has consumed some 150–200 litres of freshwater (European Environmental Agency, 2001). Yet, household water consumption is a mere teaspoonful in a bathtub when compared with the amount of water used by agriculture and industry. The USA alone uses more than 500 billion litres of freshwater every day to cool electric power plants, and roughly the same amount is needed to irrigate crop fields (Hightower & Pierce, 2008).

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In striking contrast, more than one billion people in developing nations do not have access to safe drinking water and two billion do not have adequate sanitation (World Health Organization/United Nations Children's Fund, 2005). These figures are expected to increase in the near future. Climate change, demographic expansion in developing countries and the economic development of densely inhabited areas—notably in China and India—are anticipated to cause water shortages not only for health and sanitation, but also increasingly for agriculture and industrial activities. By 2050, the demand for water for food production is predicted to double in order to cope with the needs of the growing human population (Rockström *et al*, 2005). The global need for energy production—and therefore water—is also projected to rise by 57% by the year 2030 (Hightower & Pierce, 2008). Clearly the time has come to address the central question: "Is there enough water to sustain our wasteful lifestyle?"

According to the Food and Agriculture Organization of the United Nations (FAO; Rome, Italy), our planet holds approximately 1,400 million km$^3$ of water (FAO, 2002). However, almost 98% of this is held in the oceans, and only approximately 45,000 km$^3$ (0.003%) of freshwater is available for drinking, hygiene, agriculture and industry. Most of these freshwater resources are extremely difficult to capture because the water is locked in the frozen ice caps of the poles; so in practice, only 9,000–14,000 km$^3$ is available for human use (FAO, 2002).

This is not the only limitation, however. Often, water quality is not sufficient for human consumption; moreover, it is not equally distributed: some regions have a dire lack of water, whereas others have too much. Globally, we are increasingly seeing shortages of freshwater and competition for dwindling sources. This development has alarmed scientists, economists, philosophers and politicians enough that they now seek to address the "inefficient and irrational uses of water resources worldwide," according to Vaclav Smil, from Manitoba University, Canada, at The Fourth World Conference on the Future of Science: Food and Water for Life, which was held in September 2008 in Venice, Italy.

The conference aimed to propose and discuss ways and methods of using freshwater more efficiently and fairly. As the Conference President, Umberto Veronesi, founder and Scientific Director of the European Institute of Oncology (Milan, Italy), commented, the mission of the conference was not only to assess and lament the unjust distribution of water and food resources, but also "to look forward, and to propose concrete and sustainable solutions to alleviate the pressing global problems of food and water scarcity." This article highlights some of the most innovative and provocative ideas related to water management and water policy.

Although food and water are equally essential for human life, we treat these two resources differently. Food is usually regarded as a limited economic commodity, as shown by the sharp rises in food prices in 2008. Water, by contrast, is generally seen as a free resource and one that governments should ensure citizens have unlimited access to. This idea has direct practical consequences for the current management of water supplies. "One reason fresh water has become so scarce in many parts of the world is that it hasn't been priced properly. People pay the cost of 'extraction', but the rent component in the final price is missing," commented Partha Dasgupta from the University of Cambridge in the UK. In Spain, for example, farmers typically pay only approximately 3% of the actual value of the water they are using. This raises the question of whether a more realistic price for water would lead to an overall reduction in water consumption.

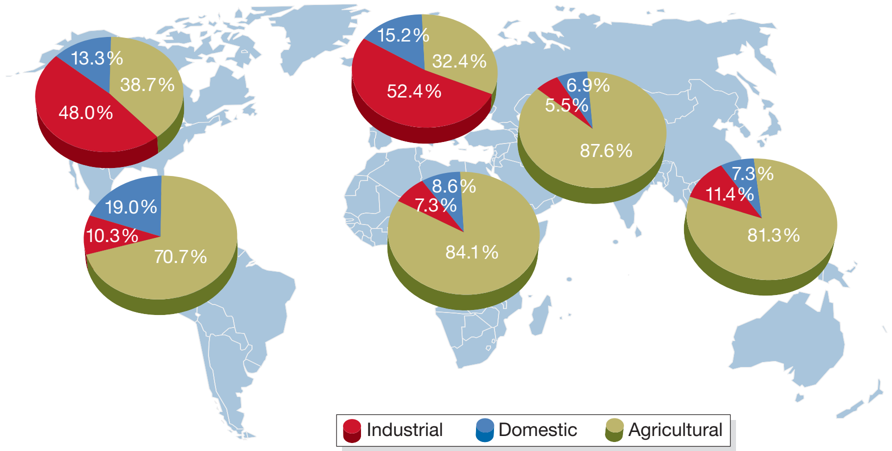

**Fig 1** | Breakdown of water use in developed and developing countries. Reproduced from FAO (2007).

**Table 1** | Average virtual water content of selected food products

| **Product** | **Virtual water content (l)** |
|---|---|
| 1 cup of tea (250 ml) | 35 |
| 1 cup of coffee (125 ml) | 140 |
| 1 glass of beer (250 ml) | 75 |
| 1 glass of wine (125 ml) | 120 |
| 1 tomato (70 g) | 13 |
| 1 potato (100 g) | 25 |
| 1 apple (100 g) | 57 |
| 1 slice of bread (30 g) | 40 |
| 1 plate of rice (100 g) | 340 |
| 1 egg (40 g) | 135 |
| 1 glass of milk (200 ml) | 200 |
| 1 slice of cheese (100 g) | 500 |
| 1 chicken breast fillet (200 g) | 780 |
| 1 pork steak (200 g) | 960 |
| 1 beef steak (200 g) | 3,000 |

Adapted from Chapagain & Hoekstra (2004)

Since 1992, when water was declared to be an economic good in the International Conference on Water and the Environment (ICWE) Dublin Principles (ICWE, 1992), the call for higher water prices and for more trade in water has gained consensus (Saleth, 1997). This perception has been reflected in influential magazines; *The Economist*, for example, reported that "the best way to deal with water is to price it more sensibly" (Anon, 2003). In addition, it will become increasingly necessary to use water rationally, particularly in developed countries, for example, by avoiding the use of drinkable water for personal hygiene or cleaning dishes.

For the rest of the world, however, higher prices to reduce the wasteful use of water in advanced economies might not be the optimal solution. In developing countries, agriculture accounts for by far the greatest consumption of water, totalling more than 70% of all withdrawals (Fig 1; FAO, 2007). In these regions, access to irrigation is central to crop productivity, food security and the livelihoods of small farmers. Nevertheless, irrigation practices are usually inefficient, with nearly half of the water being lost through evaporation and transpiration from crops.

The direct effect of higher water prices on overuse and inefficiency has been investigated thoroughly by Isha Ray from the Energy and Resources Group at the University of California (Berkeley, CA, USA). Ray conducted case studies in rural areas of India, Sri Lanka and other developing countries, and found that higher water fees might induce farmers to reduce water consumption, perhaps by switching to less water-demanding crops. However, Ray found that prices would have to be raised by several hundred per cent before they could seriously influence farmers' choices. Therefore, under these circumstances, higher water prices would not guarantee efficiency, and might even have negative consequences for equity and local food security. In addition, although significant price increases would be politically unpopular, acceptable price increases would be economically insignificant (Ray, 2005).

According to Ray, an alternative and more effective step towards the more rational and sustainable use of water in developing countries would be the enforcement of simple allocation rules—such as per-hectare rations—that would make the scarcity of water immediately obvious. In Ray's view, therefore, restriction rather than higher prices represents a more suitable strategy for farmers in developing nations, as it would "directly force farmers into potentially more efficient water use patterns" (Ray, 2005).

Water-pricing reform and water-allocation rules are obvious solutions, but their implementation might not always be straightforward. Both strategies have to be enforced on a local scale by appropriate institutions, and have to be specifically designed for their physical, social and institutional context (Johansson *et al*, 2002). However, there are some success stories in which farmers and small holders have been involved directly in the management of water allocation and irrigation systems. In South Africa, for example, so-called catchment-management agencies were formed as a result of the South African Water Act of 1998 and allow all interested parties to participate in water management. Similarly, in Mexico, the management of more than 85% of the 3.3 million hectares of publicly irrigated land has been taken over by farmers' associations, most of which are now financially independent (FAO, 2002). Reforms of water policies require transparency and accountability, both to their end users and to society. Water institutions, particularly those involved with irrigation, should be legally bound to provide information about how water is used, by whom and in what quantities.

Every bite into a juicy apple yields 80–100 grams of water contained in its flesh. What most of us do not realize, however, is that we are consuming more than 50 'virtual litres' of water that were used to produce the apple. 'Virtual water' is an emerging concept in water policy that refers to the volume of freshwater used to produce a given economic good—not necessarily a food product (Allan, 1993, 1994). The adjective 'virtual' emphasizes the fact that most of the water used in the various steps of the production chain is not contained in the end product.

If the daily drinking water requirement per person is 2–4 litres, the water needed to produce the daily food requirement for an individual amounts to 2,000–5,000 litres (FAO, 2002). It takes 500 litres of water to produce 500 grams of wheat, 1,000 litres of water to produce 1 litre of milk and more than 4,500 litres of water to produce just 300 grams of beef (Table 1; Chapagain & Hoekstra, 2004). If we add to these figures the amount of water that is consumed to produce all the other goods that we use in our daily lives, the result is what water management specialists call the 'water footprint' of a person—a concept that is similar to the 'carbon footprint'. In technical terms, the water footprint of a person is defined as the total volume of water that is used to produce the commodities, goods and services consumed by that person. Of course, the concept can be extended to a much larger scale, for example, to consider the water footprint of a company, a region or an entire nation.

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The water footprint (www.fao.org/nr/water/aquastat/data/query/index.html) is more accurate and provides a more useful assessment of the water demands of a country than the national figures for water consumption. Many goods that are consumed by the inhabitants of one country were produced by other countries, which implies that the real water demands of a population are often much higher than the actual national water withdrawal—and that enormous amounts of virtual water cross national boundaries. The USA has the largest water footprint, consuming a total of 2,480 $m^3$ per year per capita. It is closely followed by southern European countries such as Greece, Italy and Spain, which use approximately 2,300–2,400 $m^3$ per year per capita. At the other end of the scale, China has a relatively low water footprint, with an average of 700 $m^3$ per year per capita (Chapagain & Hoekstra, 2004).

Economists and water-management experts at The Future of Science conference suggested three possible strategies for reducing water footprints. The first strategy would be the adoption of more sustainable production processes that require less water per unit of product. In developing countries, this would mean the more efficient use of water in agriculture, whereas more advanced nations would reduce water consumption in industry and energy production. Claus Conzelmann, Vice President for Safety, Health and Environment at Nestlé (Vevey, Switzerland), reported that the company has implemented new water-management policies to improve water efficiency in its manufacturing processes. According to Conzelmann, the total volume of water needed by Nestlé factories consequently dropped from 218 billion litres in 1998 to 155 billion litres in 2006, despite a significant increase in the quantity of products manufactured.

The second strategy would be a shift towards less water-intensive consumption patterns. Even moderate changes in diet can have a significant impact; for example, the consumption of meat makes a significant contribution to a high water footprint because meat is the most inefficient food to produce in terms of energy and water demand—which partly explains the high water footprints of countries such as the USA, Canada, France, Spain, Portugal, Italy and Greece. The average meat consumption in the USA, for example, is 120 kg per year, which is more than three times the world average. "If we could reduce the consumption of meat by 20%, we could save 50% of the water currently used for feed production," Smil noted.

Other countries will face the same challenge in the near future. "Global population and per capita revenues are predicted to increase by 50% and 40%, respectively, during the next 50 years," explained David Tilman from the University of Minnesota in the USA, who pointed out that as their income increases, people in many countries are changing their diet to include more meat and eggs. The consequent increase in demand for maize and coarse grains as animal feed has significantly enlarged the water footprint of these nations.

The third strategy to reduce water footprints would involve a reorganization of global trade. The production of water-intensive foods such as wheat, rice and meat should be concentrated in those nations with large water reserves, whereas countries with little water productivity should reallocate resources to agricultural and industrial activities that are better suited to dry areas (Chapagain *et al*, 2005). One of the few countries that has addressed this problem is Jordan: instead of aiming at self-sufficiency, Jordan has externalized its water footprint by importing wheat and rice from the USA.

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Given that there are valid ways to reduce water footprints, whose responsibility should it be to encourage or enforce a shift towards more sustainable agricultural and industrial products? What is the right balance between state intervention and individual choice? John Krebs from Jesus College (University of Oxford, UK) proposed a gradual implementation of public interventions as the most appropriate strategy: a hypothetical 'intervention ladder'. The bottom rung would involve public institutions promoting educational programmes about water consumption and nutrition. New marketing and labelling regulations could then help consumers to choose healthier and more sustainable products, while the attitudes of consumers could be influenced by the taxation of resource-intensive commodities. As a final step, bans or other regulations could be implemented to restrict choice.

However, water shortages are not the only problem. As Susan Murcott from the Massachusetts Institute of Technology (MIT; Cambridge, MA, USA) reported, some regions have enough water but it is not suitable for human consumption. In fact, an estimated 884 million people, mostly in rural areas and in urban and peri-urban slums, do not have access to clean drinking water, but rather rely on 'unimproved' water supplies. Such microbially and chemically unsafe water harbours the risk of many diseases, including diarrhoea, dysentery, cholera, Guinea worm, arsenicosis, and skeletal and dental fluorosis. In fact, estimates indicate that access to safe water could reduce diarrhoeal and other enteric diseases by up to 50%, even in the absence of improved sanitation or other hygiene measures (Nath *et al*, 2006).

**Fig 2** | The Kosim system. This consists of a ceramic pot filter that removes soil debris and microbiological contaminants from the water. The appearance of water from an earthen basin located in the Gonja District (Northern Ghana) is shown before (right) and after (left) the Kosim sanitation step. Picture courtesy of S. Murcott.

One solution to the problem of water scarcity and pollution has therefore been the application of household water treatment and safe storage (HWTS) systems, which are a cluster of innovative, low-cost technologies developed by Murcott and her colleagues in non-governmental organizations: the Environment and Public Health Organization (ENPHO; New Baneshwor, Nepal), and the Centre for Affordable Water and Sanitation Technology (CAWST; Calgary, Canada). HWTS systems are simple, self-reliant and user-friendly, and can be used locally, such as the Kanchan arsenic filter (KAF) that is being used in Nepal, where arsenic and microbial contamination of drinking water pose a serious health problem. Murcott reported that the KAF reduces arsenic contamination by 85–90% and total coliform contamination by 85–99%; 7,000 of the 30,000–40,000 households identified as being affected by arsenic contamination are now using KAFs, and another 5,000 will install the system in the next year. This cheap household system is also being used in other countries around the world.

Another example is the Pure Home Water social enterprise in Ghana that distributes containers for safe water storage, methods for disinfection and Kosim filters: ceramic pot filters that remove microbiological contaminants (Fig 2). Pure Home Water currently reaches 100,000 people and the Kosim filters both reduce the risk of diarrheal illness and are culturally compatible, which means that they are well accepted by target communities—an important prerequisite for the introduction of a technological improvement. Murcott emphasized the necessity to support and disseminate these methods, as they are simple and cheap, and have the potential to be “part of the solution that provides safe drinking water in the next decades to the one billion people at the bottom of the pyramid.”

Freshwater is a precious resource, but the remaining water on the Earth—more than 97% of which is saline water—goes untapped. “The world is not short of water, it is just in the wrong place and is too salty,” commented Charlie Paton from Seawater Greenhouse (London, UK). “Converting seawater to fresh water in the right places offers the potential to solve these problems.” However, large-scale desalination plants typically use large amounts of energy and require expensive infrastructures, so they are unlikely to be deployed on a large scale in the foreseeable future. Paton calculated that 1–3 kg of fossil fuels is required to produce 1,000 kg of water, which, in turn, generates just 1 kg of crop.

Paton therefore presented the Sahara Forest project as an alternative method for producing freshwater, food and renewable energy in hot, arid regions, and as a means for revegetating desert areas. The project combines two established technologies: concentrated solar power and the ‘seawater greenhouses’ that are being built in Tenerife, Abu Dhabi and Oman. Concentrated solar power uses mirrors to concentrate sunlight to generate heat, which is then used to boil water to drive conventional steam turbines that generate electricity.

Seawater greenhouses are constructed in such a manner that evaporators cool and humidify hot air using seawater (Fig 3). This cooled air provides good climate conditions for the crops that are grown inside the greenhouse, as it reduces their transpiration by up to 80%; this reduces the need for irrigation and improves crop yield because the plants are not stressed by excessive transpiration. As the air leaves the greenhouse area, it is cooled down by cold deep-sea water; the humidity condenses out of the airstream and can be collected as fresh water.

Seawater greenhouses use relatively little electrical power because most of the thermodynamic work of cooling and distilling water is performed by the Sun and the wind: 1 kW of electrical energy used for pumping sea water can remove 800 kW of heat through evaporation. The evaporators are also effective air scrubbers and, in combination with salt water, have a biocidal effect on airborne contaminants and pests that reduces the need for pesticides inside the greenhouse.

The quantity of seawater that evaporates through the seawater greenhouse system is ten times greater than that which evaporates from an equal area of land covered by grass. According to Paton, seawater greenhouses produce more than five times the amount of fresh water that is needed by the plants inside. The excess water can be used outside the greenhouses to grow hardier plants such as jatropha, an energy crop that can be turned into biofuel. The Sahara Forest project therefore creates a microclimate of cooler and more humid air around the greenhouses, which allows plants to be grown outside and increases the potential for precipitation through the formation of dew or rainfall, thereby allowing further

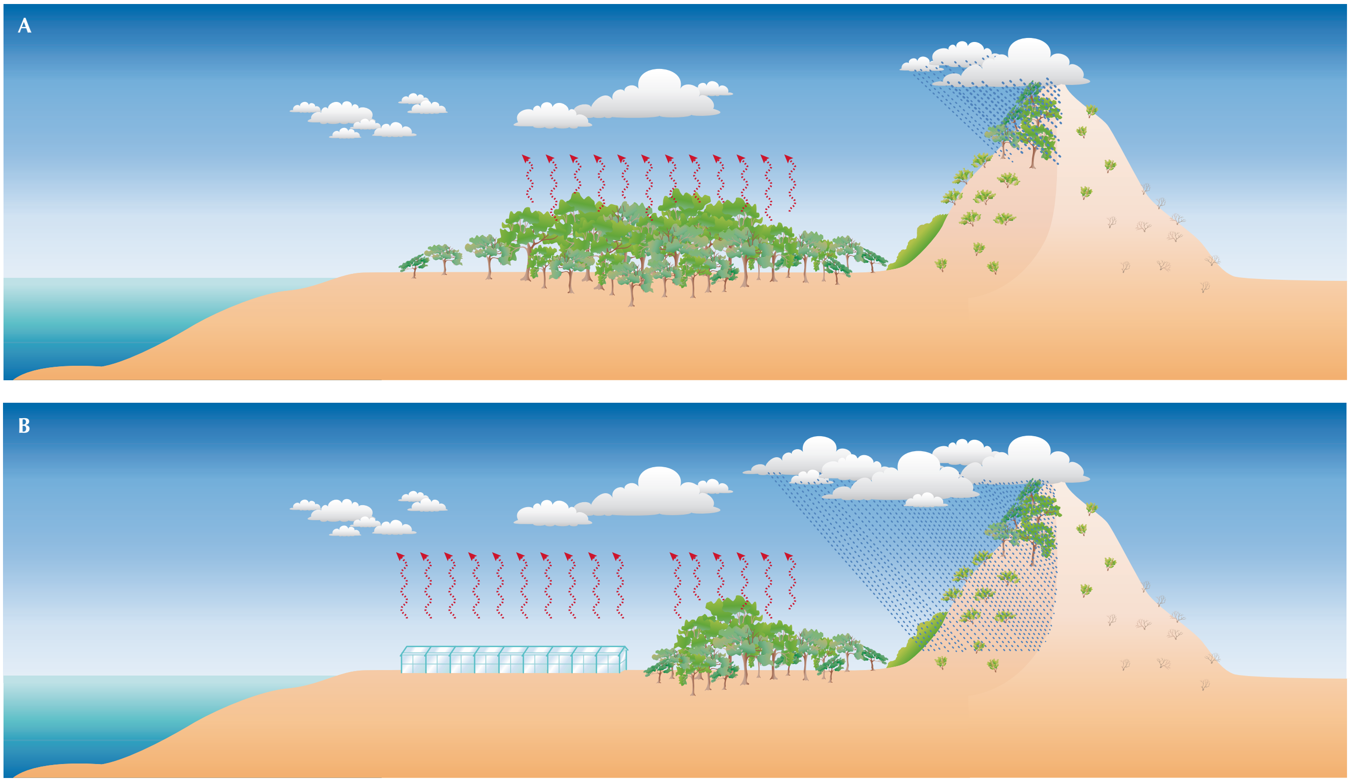

**Fig 3** | Schematic representation of the effects on climate in an inland desert. (**A**) Effect of a forest. (**B**) Effect of a series of greenhouses. Red arrows represent the water vapour produced by plants and greenhouses. The greenhouses use freshwater derived from the evaporation of large volumes of seawater. The resultant humidity provides water for plants within and outside the greenhouses, and increases the potential for precipitation through the formation of dew or rainfall. Pictures courtesy of C. Paton, reproduced with minor modifications.

areas of desert to be revegetated (Fig 3). The greenhouses of the Sahara Forest project would be constructed in a manner that would provide a windbreak for the outdoor fields and would include concentrated solar power arrays to generate electricity.

In April 2000, Kofi Annan, then Secretary General of the United Nations, called for a 'blue revolution' in agriculture that would generate "more crop per drop" (FAO, 2002). Although the 'green revolution' of the twentieth century markedly increased crop production through genetic improvements of major food crops, increased mechanization, improved pest control and improved soil fertility, the challenge for the blue revolution in the twenty-first century is to provide enough water to produce food for an additional two billion people. This will require, among other things, an expansion of irrigated areas (as irrigation can increase crop yields by 100–400%), the use of more efficient irrigation systems and various techniques to harvest rainwater (FAO, 2002).

Other strategies to save water would concentrate on plants, as water requirements depend on the crop that is grown; rice, for example, uses around twice as much water per hectare as wheat. The blue revolution is therefore also a great challenge for breeders and plant biotechnologists to improve water use by crop plants, as well as plant performance and yield under drought conditions. Although breeders have taken a traditional approach by crossing varieties and selecting the progeny based on their ability to deal with stress, plant biotechnology has by far the greatest potential for future improvements. This would require the identification of the key genes involved in water use and drought tolerance, and the modification of one or more of these genes to obtain the desired phenotype. A few dozen such genes have already been identified and various genetically modified drought-tolerant crop plants are in the pipeline for commercialization.

Many studies in this field have been performed in the model plant *Arabidopsis thaliana*, the genome sequence of which was published in 2000 (The Arabidopsis Genome Initiative, 2000). These studies have shown that multiple complex pathways are involved in controlling plant drought responses, and that engineering a single trait is not always a promising strategy. Instead, transcription factors—proteins that act as master regulators of cellular processes—are excellent candidates for manipulating the modification of complex traits—such as the avoidance of dehydration in crop plants—and transcription factor-based technologies are likely to become a major part of the next generation of genetically modified crops. The engineering of stomatal activity, for example, is a promising approach to reduce the water requirements of crops and to enhance productivity under stress conditions (Schroeder *et al*, 2001). An example of the successful modification of a transcription factor involved in stomatal activity has already been reported (Cominelli *et al*, 2005).

Access to water is a universal human right. Unfortunately, resources are dwindling while wasteful and inefficient practices remain pervasive. To address these problems new practices need to be enforced: practices that are embraced by the political establishment and are in the best interests of the public. This will mean giving a realistic value to the price of water and incorporating new technologies in agriculture, probably including genetic modification to generate water-efficient crops.

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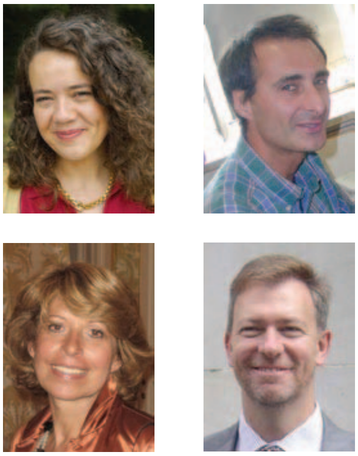

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