Green, blue and grey waters: Minimising the footprint using soil physics

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Abstract
Virtual water is the water embodied in products. It comprises the green water of rain transpired by the plant, the blue water added as irrigation, and the grey water contaminated by agrichemicals. Biophysical knowledge of green-water use by plants, when complemented with soil physics modelling of both blue and green water flow in soils, permits development of irrigation practices and policies to protect the natural capital stocks of our opportunity-rich blue-water resources that are used for irrigation. Modelling of leaching processes is leading to practices for limiting grey water. These tools and techniques will lead to eco-efficient practices to reduce the virtual water content of the food, fibre and fuel products we grow, while maintaining other ecosystem services that are water dependent.

Key Words
Water footprint, virtual water, irrigation, climate change, ecosystem services, food

Introduction
The *Guardian Weekly* noted in 2002 that "water is now known as 'blue gold' … and 'blue gold' is this century's most urgent environmental issue". Even more recently, *The Economist* (18 September, 2008) asserted, in an article on water for farming entitled "Running dry", that "… the world is facing not so much a food crisis as a water crisis'.

Many of the world's regions are currently experiencing water stress, as measured by the fraction of water withdrawals to that available. The IPCC Special Report on Emissions Scenarios of 2000 considered future climate change impacts. Scenario A1B is a moderate scenario in terms of the global rise in temperature. In Figure 1 below are shown the projections by the IPCC in 2007 for the change in annual water runoff, which is a metric of water availability, in terms of percentages for 2090-2099, relative to 1980-1999. The world's key agricultural regions of California, Mexico, Chile, Argentina, the Mediterranean, South Africa and Australia are destined to suffer even greater water stresses than are presently being felt. Water will assuredly become scarcer and more valuable, such that its management will call for better scientific knowledge about the functioning of agricultural soils.

The Economist (18 September, 2008) found that some 70% of the world's water consumption is used in farming and that there is a pressing need to make it go further, by developing knowledge and tools to monitor water-use efficiency. It concluded that indeed "… farming tends to offer the best potential for thrift".

Water for irrigation to overcome droughts and nutrients applied in fertilisers for enhanced plant growth, are key inputs for most modern and intensifying production systems. Some 40% of the world's food comes from 20% of our lands - thanks to irrigation. One third of the world's population relies on food whose production comes directly from the use of nitrogenous fertilisers. Measurement and modelling of water use by pastures and crops will provide the basis for the development of thrifty options, and shrinking the virtual water content of agricultural products.

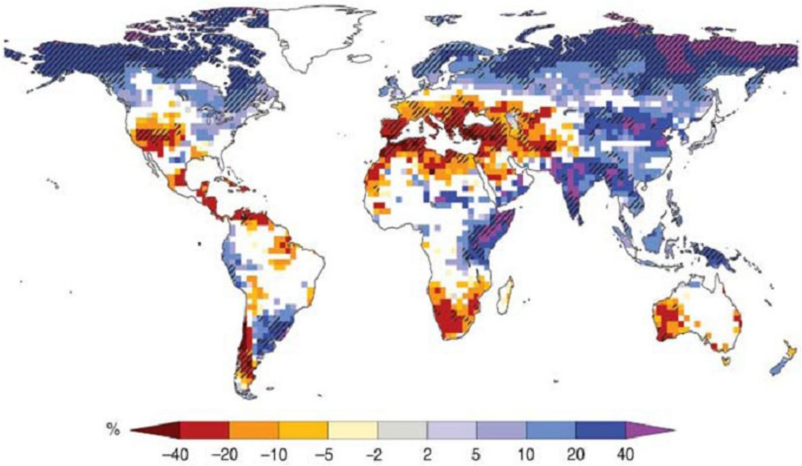

Figure 2. The Intergovernmental Panel on Climate Change (IPCC) projection for the global change in water availability at the end of the 21st century under their moderate scenario A1B.

Virtual Water

Virtual water, first defined by Allan (1998), is the volume of water used to make a product, and is the sum of the water use in the various steps of the production chain. Virtual water comprises three components of different colours: the green, blue and grey waters.

Green water is the water transpired by the plant that comes from rain water stored in soil. Blue water is the water in our surface and groundwater reservoirs. In irrigated agriculture, blue water is abstracted to maintain transpiration. It is imperative that it is used with a high level of efficiency. Soil is a storage reservoir for the green water that falls from the sky, or that which has been added through irrigation from blue-water reservoirs. Grey water is the water that becomes polluted during production, say in agriculture because of the leaching of nutrients and pesticides. Grey-water volume can be quantified by calculating the blue water that would be required to dilute the receiving water body to an acceptable quality standard.

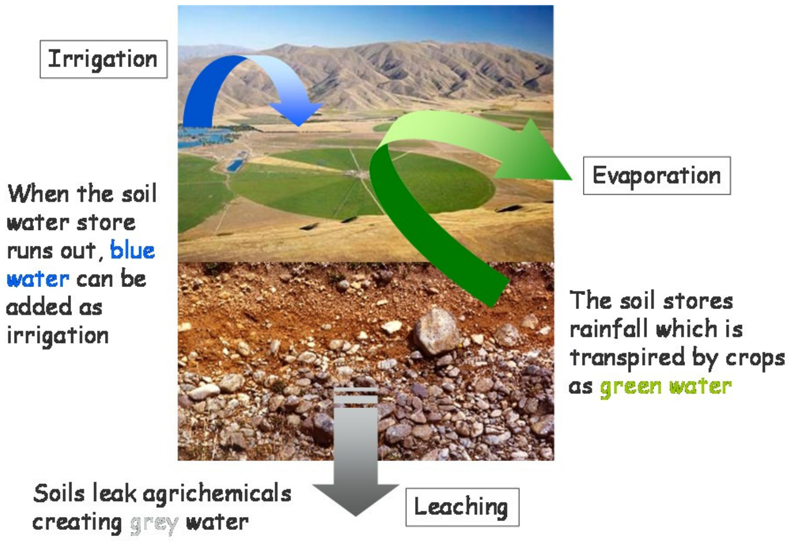

Figure 2. The three colours of water: green water being evapotranspired rainwater from soil, blue water used for irrigation and grey water contaminated by agrichemicals.

Shrinking the water footprint of agriculture can be achieved using practices that reduce the virtual water content of the food, fibre and fuel products. For a country, reducing the water footprint can reduce the total human appropriation of the nation's natural capital stocks of water used for the provisioning service provided by irrigation. This will ensure that requisite amounts of national waters are preserved for environmental flows to maintain the supporting, regulating and cultural services provided by water.

Maximising utility: Green water use

Soil physical and plant biophysical knowledge can be used to develop practices to maximise the utility of green water. Canopy management can, especially with horticultural crops, reduce levels of green-water use through transpiration by limiting vegetative vigour. In Figure 3 the pattern of green-water transpiration is measured directly by sapflow within the stem of a grapevine using the heat-pulse technique (Green *et al.* 2008). Also shown there is the prediction of vine water-use using a biophysical model of transpiration. Green water use by the vine rises in spring after bud burst, and then it is limited in summer by hedging of the vines, plus leaf plucking and the use of deficit irrigation to limit vegetative vigour.

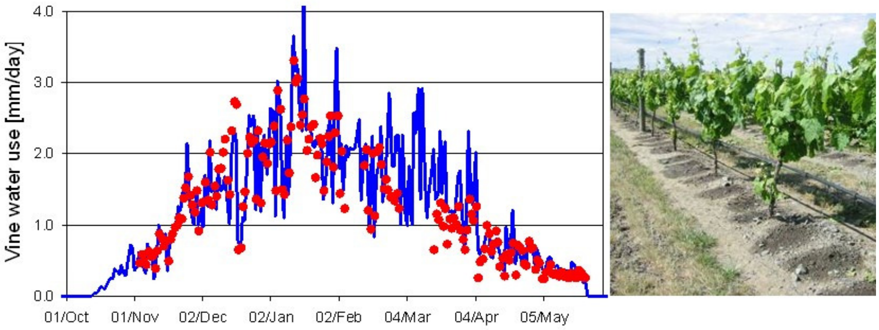

Figure 3. Measured daily grapevine transpiration using sapflow devices (red dots) in relation to a biophysical model of plant transpiration (blue line) based on ambient weather, soil physics and the changing leaf area of the vine.

Minimising irrigation: Blue water abstraction

Irrigation, blue water use, is only required when the green water store in the soil runs short. The soil's ability to store green water is determined by the physical characteristics of the soil. Soils that can store more green water will have a higher natural capital value and thus should be favoured, and protected for primary production. Soil physicists have long studied the ability of soil to store water, and our understanding of green water storage is good.

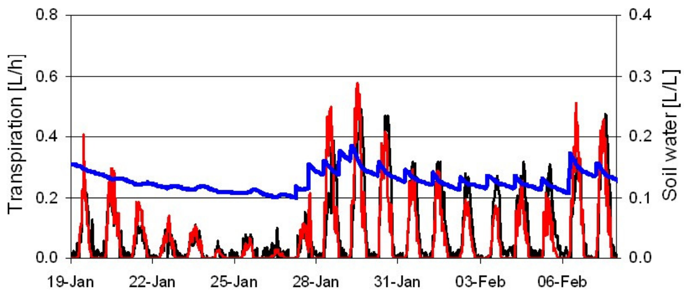

Figure 4. Measured soil water content (blue) and its impact on measured grape vine transpiration (black). The modelled plant transpiration is also shown (red)

What is less well understood is the biophysics of how plants extract water from this store, and we lack clear determination of when blue-water is needed. With limited water resources now being allocated to irrigation, relative to allocation for other ecosystem services, deficit irrigation practices are becoming more common. To manage irrigation efficiently, and to manage deficit irrigation effectively requires a high degree of understanding of soil physics and plant biophysics. New measurement techniques and modelling schemes are enabling the development of practices to minimise blue water use and reduce the virtual water contents of our primary products. In Figure 4 we show how the decline in soil water past the critical point can affect grape vine transpiration, and how rewetting of the soil can restore plant functioning. The key is to use the minimum of blue water to achieve the desired response in the plant – here, grape berries of high quality

Minimising leaching: Grey water production

We have comprehensive soil physical modelling schemes to predict the leaching of agrichemicals. But for the grey water volumes, there is a dearth of measurements available to corroborate our modelling. New measurements are providing us with the vision that is needed to provide our models with credibility, as well as defendability since non-point source pollution issues are inexorably making their way to the courts. Flux meters are one such new tool (Gee *et al.* 2009), and a version of these is shown in Figure 5

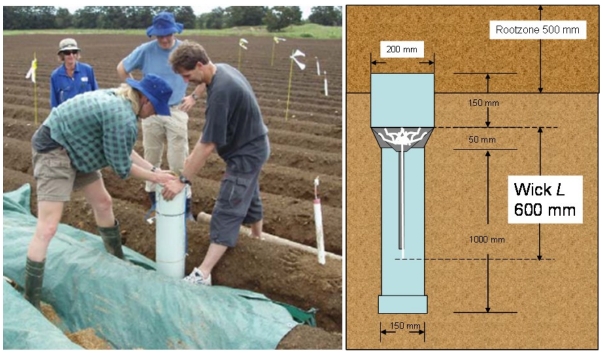

Figure 5. Installation of a fluxmeter into a field of potatoes (left), and the internal system of a fluxmeter showing the wick whose length *L* controls the suction at the soil interface, and the underlying reservoir to collect samples for analysis of leachate quality.

Conclusions

Quantitative soil physics modelling is a valuable means by which we can organise the new knowledge that arises from our better measurements and monitoring in the root zone. This can then be applied to minimise the green, blue and grey waters used in irrigated agriculture. From our new understanding we can develop policies and implement actions to protect the natural capital value of the ecosystem goods and services provided by our plant, soil and water systems. This will ensure sustainable and eco-efficient production from irrigated agriculture by minimising the virtual water content of our food, fibre and fuel products.

References

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