Institution: Lancaster University

Unit of Assessment: UoA7- Earth Systems and Environment Sciences

Title of case study: Optimising crop production and sustainable irrigation technologies in water scare regions through the application of plant signalling science

1. Summary of the impact (indicative maximum 100 words)

The limited availability of water for use in agriculture is one of the greatest threats to global food security. Food production depends increasingly on agriculture in areas where water is in short supply. Lancaster science has led directly to the development of new crop management techniques to allow immediate and cost-effective increases in water-efficient production by farmers in water scarce regions. The novel irrigation techniques developed from Lancaster research have had multiple positive impacts on water use efficiency in agriculture on several continents, most reliably quantified in northern China. Longer term impacts of these technologies in drought-prone regions across North West China have led to large-scale improved environmental quality, for example in terms of raised water tables.

2. Underpinning research (indicative maximum 500 words)

Fundamental research in to plant physiological ecology undertaken at Lancaster from the mid-1990s revealed for the first time how plants regulate their growth and physiology under drought conditions as a function of water availability in the soil. The Lancaster team, led by Prof Bill Davies CBE and, until his retirement in 2001, Prof Terry Mansfield FRS, showed that soil water status sensed by the roots is communicated to the shoots via long distance chemical signalling[1]. This information allows the plant to regulate gas exchange, including water loss via transpiration, and growth as a function of water availability[2]. Davies and his team (including Jianhua Zhang, David Gowing, Carlos Trejo and Francois Tardieu) developed an entirely new experimental technique, the split-root method that allowed the impact of chemical signalling to be separated from that of altered water supply to the shoot. The Lancaster team went on to use this technique to:-

(i) demonstrate unequivocally that chemical signals were central to root-to-shoot communication[3] and then

(ii) identify abscisic acid as a dominant chemical signalling molecule responsible for root-to-shoot signalling under drought conditions[4]. These advances in the fundamental understanding of plant signalling subsequently led to:-

(iii) new insights in to the importance of chemical signalling under environmental stress [5]. Finally, this led us, and others, to recognise

(iv) that new understanding of the effects of signalling science could form the basis of new techniques in agricultural irrigation.

These new irrigation techniques, specifically Partial Root Drying (PRD)[2] and Alternate Wetting and Drying (AWD)[6], are the key element in the impact of our research (see Section 4).

Our fundamental research has made a seminal contribution to its field with references to Davies' papers during this period totalling more than 10,000 in ISI Web of Knowledge. The same research has led to a very significant body of translational research showing how fundamental plant physiological ecology can be exploited to sustain/enhance crop yields and increase water productivity in several parts of the world where sustained food production under drought is crucial if we are to feed an ever expanding world population. Our contribution to this field is highlighted in a paper by Kang and Zhang (J. Exp. Bot. (2004): 2437-2446) which is not only highly influential recent research in the field, but has also guided crop management practitioners in many parts of the world (see Section 4). Our research has also influenced the wider global research agenda in relation to food security, for example in our contribution to the 2011 Foresight report[6].

3. References to the research (indicative maximum of six references)

The three references most influential in the impact are shown with an *

1. *Tardieu, F. and Davies, W.J. (1993). Integration of hydraulic and chemical signalling in the control of stomatal conductance and water status of droughted plants. *Plant, Cell and Environment* **16**, 341-350.

2. Davies, W.J., Wilkinson, S. and Loveys B. (2002) Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. *New Phytologist* **153**, 449-460

3. *Gowing, D.J.G., Davies, W.J., Trejo, C.L. and Jones, H.G. (1993) Xylem-transported chemical signals and the regulation of plant growth and physiology. *Philosophical Transactions of the Royal*

Society of London, *Series B* **341**, 41-47.
4. *Trejo, C.L., Clephan, A.L. and Davies, W.J. (1995). How do stomata read ABA signals? *Plant Physiology*, **109**, 803-811.
5. Wilkinson, S. and Davies, W.J. (2002) ABA-based chemical signalling: the co-ordination of responses to stress in plants. *Plant Cell and Environment* **25**, 195-210.
6. Davies, W.J., Zhang. J., Yang, J. and Dodd, I.C. (2011) Novel crop science to improve yield and resource use efficiency in water-limited agriculture. *Journal of Agricultural Science* **149**, 123-131.

4. Details of the impact (indicative maximum 750 words)

Over a period of twenty years our fundamental research into root-shoot signalling in relation to drought has informed the development of a range of technologies through which our science has been applied to deliver environmental and commercial benefits in crop production[A]. Key elements of this translational work have been undertaken directly by Davies and his team at Lancaster. This is reflected in the diversity as well as the scale of external support for our research, which has won support from multiple funders totalling more than £3M, including DEFRA (2003, 1.2M; 2006, £100K; 2009, £220K), EU (2000, €400K, 2009, €220K, 2010, €495K, 2011, €1.2M), CIMMYT 2012 $1.2 M and HDC (2008, £70K and £28K). This funding has been based on our international network of more than 30 research collaborations and 20 partnerships with companies[A].

The global significance and reach of the impact from our fundamental research (Section 2) is amplified through the translational research undertaken by others working with Lancaster. There are many examples[A], however we will focus here on examples from Australia and, especially, China. This is summarised in the following timeline of some of the key developments:

- **1993** – Publication of Lancaster research in to long distance signalling (described in Section 2) identifying the key mechanisms of root-to-shoot signalling
- **1996** –Dr Jianhua Zhang (now at Hong Kong Baptist University after completing his PhD and post-doctoral research within Davies' group in LEC), in collaboration with Prof Shaozhong Kang at Chinese Agricultural University, wins funding to apply Lancaster research to develop new irrigation approaches in Chinese agriculture (HK$ 858,000 from the Croucher Foundation)[B].
- **1997** - First Kang and Zhang paper describing their Deficit irrigation research in China (Kang et al 1997). Controlled alternate root-zone irrigation: a new approach for water saving in farmland. Ag Research in Arid and Semi Arid Areas. 15, 1-6 (in Chinese)
- **1997** – Initial application of alternate root-zone irrigation in Gansu province[C]
- **1998** – Translational work based on Partial Root Drying (PRD) by researchers at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) results in first publication of the benefits of this irrigation technique in wine production[D]
- **2000** – Building on their 1997 paper, and highlighting its origins in Davies' work, Kang and Zhang describe "Alternate furrow irrigation" as a "low tech" method of delivering PRD in arable crops (Agricultural Water Management, 45, 267-274) and conclude that the method has "*significant value in arid areas with shrinking water resource*"[E].
- **2003 –** A report commissioned by Australia's National Program for Sustainable Irrigation, highlights the use and future prospects of regulated deficit irrigation and partial root-zone drying in wine production.[F]
- **2004** – Davies and Kang co-organize a workshop on Water Saving Agriculture in Yangling China, attended by more than 500 Chinese researchers and irrigation end-users.
- **2008** - Zhang's key role in improving irrigation practices in Chinese agriculture leads him to being listed by Nature in 2008 as one of 'Five crop scientists who can change the world'. Marris (Nature 2008)[G] writes "*Zhang moved to Hong Kong after several years at Lancaster and now travels throughout China talking about research on deficit irrigation as a way to improve agricultural efficiency…… Thanks to Zhang and others, farmers in northern China have learned to use less water. In north-west China, for example, the amount of water used for irrigation has almost halved from what it was a decade ago*".
- **2012** Kang is elected to the Chinese Engineering Academy in 2012, largely for his work on the application of Deficit Irrigation techniques in the driest regions of the country[F].

Both the Australian and Chinese researchers fully acknowledge Lancaster as the inspiration for

their irrigation work. For example, Stoll et al (2000)[H] state "*The idea of using PRD as a tool to manipulate water deficit responses in this way had its origin in the observation that root-derived abscisic acid was important in determining grapevine stomatal conductance (Loveys, CSIRO Australia) and the demonstration by three researchers, Gowing, Davies and Jones, working at the same time at the University of Lancaster with apple trees, (Gowing et al., 1993) that split-root plants could be used to show that many of the effects of water stress could be explained in terms of the transport of chemical signals from root to shoot without changes in water relations*". Kriedemann and Goodwin[G] go on to note "*We have been able to develop a commercially viable irrigation system for grapevines which had been designed to reduce vegetative vigour and improve water use efficiency. We have called the technique Partial Rootzone Drying (PRD) and it requires that the roots are simultaneously exposed to both wet and dry zones….. Implementation of the partial rootzone drying technique is simple, requiring only that irrigation systems are modified to allow alternate wetting and drying of part of the rootzone. Commercial-scale trials are currently being evaluated and further studies on the physiological mechanisms involved in modifying water use efficiency in a range of horticultural plants is continuing"*
Work at CSIRO has continued, with Davies a collaborator in several of these consortia. While the economic focus of the wine industry in Australia has changed in recent years and driven irrigation research in another direction, progressive vineyards across three continents are deploying PRD to improve water use efficiency and wine quality[I,J].

The application of PRD and deficit irrigation more generally in China has grown quickly. Water is an especially pressing environmental, economic and social issue in China, where the population of more than 1.3 billion people, approximately 20% of the world population, depends on only 7% of the world's water supply. Almost 60% of Chinese agricultural land (approx. 69.6 m ha) is irrigated. As noted above, exploitation of Lancaster's research in China began with the joint grant to Zhang and Kang in 1996. Their research has been continuously supported by Chinese funders since that date, and LEC continues to contribute direct inputs to those research programs, via, for example, substantial RCUK support focussed on delivering our research into Asia (2008, £25K; 2009, £27K, 2012 £180k) culminating in the RCUK China Bridge in 2009 (£1.3M). Because of LEC's continuing collaboration with Kang at the Chinese Agricultural University and Zhang (recently appointed as Director of a State Key Lab in Agrobiotechnology in Hong Kong) we remain closely and directly involved with the on-going development and application of PRD-based systems in Chinese agriculture. To illustrate the reach and significance of the impacts delivered through the application of PRD-based approaches, we focus here on well quantified impacts in northern China. We are aware of the techniques being applied to improve irrigation in Gansu, Shaanxi and Xingjiang Provinces, but the best documented application comes from Gansu where environmental protection and restoration are high priorities for government, as described in the letter from the Gansu Provincial Department of Water Resource[K], "*Shiyang River Catchment is a typical ecologically fragile region with agriculture land of "no grow without irrigation". The proportion of water usage for agriculture in the area is over 90%. The water shortage and the over-exploitation of groundwater has caused serious ecological and environmental problems, such as groundwater level drop, vegetation degradation, shrinkage of oasis, desertification, and soil salinization and alkalization*." The use of PRD-based technologies in Gansu provides a focussed example, not only of impact of Lancaster research on agricultural production, but also far wider socio-economic and environmental benefits. Each of these three inter-linked areas of impact is described below.

a. Quantified impacts on crop production and resource use efficiency
Techniques arising from the further development of PRD by Kang and Zhang are now used over an area of approximately 120,000ha in the Wuwei district alone.[C] According to the Water Resource Bureau, Wuwei City "*The results for individual crops are: maize, water saving 50% with yield reduction at 11%; apple and wine grape, water saving 10-18% and 35-40% respectively with no yield reduction for both crops; cotton, water saving 30% with seed cotton yield reduction only at 5%, but with much higher quality of lint cotton yield*"[C] In other crops "*reduction of water use for tomato and chili production is 1530m^3/ha and 1920m^3/ha for winter to spring season and 180 m^3/ha and 285m^3/ha for over the winter season respectively, while the yields were maintained unchanged*"[L]. This scale of reductions in the use of irrigation water use leads to an estimated total saving of around 80-100 million cubic metres of irrigation water per annum in this one catchment alone. More recently, Prof Kang notes that similar savings have been reported in the Beijing area[E].

b Economic benefits of improved water use.

The economic benefits of using PRD-based technologies clearly varies between crop but, for example, in a case study with cotton Tang et al (2010) showed not only reduced water use but also increased quality and decreased harvesting costs, leading to a 30% increase in profit per unit water used[L]. The International Commission on Irrigation and Drainage (ICID) in recognising Prof Kang's contributions and achievements to water-savings in agriculture[M] noted "*He and Prof Zhang Jianhua (Hong Kong Baptist University) developed a new irrigation method systematically, so called controlled alternate partial root-zone irrigation (CAPRI), in 1996 to improve crop water use efficiency by exploiting the plant physiological responses to partial soil drying in their root zone*"[M] and goes on to note that farm income in one district where the technology had been applied (Hongdong in Shanxi Province) farm income increased by ¥10,566,800 (c. £1.1M at current exchange rates) due to increased yield and reduced expenditure of irrigation water, plus less obvious savings, like reduce electricity costs for pumping ground-water[M]. The research has also led to new patents[F] and commercial systems to deliver PRD and related irrigation approaches.

c. Reducing the environmental impact of agriculture.

The ICID document highlighting Kang's achievement in northern China also describes PRD-based technologies being used in grape, maize and cotton, as one of six key approaches to protect and restore the whole Shiyanghe river basin, an area about 4.16×10^4 km^2. They note that "*Due to its arid climate, limited water resources and some inappropriate water-related human activities, the area has developed serious loss of vegetation, and gradual soil salinization and desertification...*"[M] The use of PRD-based technologies have contributed to significant environmental improvements, for example ".. *the groundwater level of Qingtu Lake on the downstream Shiyang River raised 0.17 metre compared with that in 2007, a significant improvement in ecological environment*".[K] Water not used in agriculture has been used to irrigate the Gansu national ecological security barrier, supporting the re-establishment of native vegetation.

Although northern China provides the most advanced and quantifiable examples of the multiple environmental and economic impacts of PRD-based approaches, the methods are now increasingly being adopted in other parts of China, in southern Europe and elsewhere. The documented reach and significance of the benefits of PRD in in China and elsewhere highlight the potential scale of impacts as the technique becomes established in other regions...

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. LEC website (http://www.lancaster.ac.uk/lec/research/research-areas/plant-and-crop-science/)
B. Letter from Director of State Key Laboratory of Agrobiotechnology, Chinese University of Hong Kong 27/6/ 2013 (Chinese original with English translation)
C. Letter from Water Resource Bureau, Wuwei City dated June 20th 2013 (Chinese original with English translation)
D. Loveys BR.1998. Factors influencing grapevine vigour and the potential for control with partial root-zone drying. Australian Journal of Grape and Wine Research 4, 140–148.
E. Letter from Academician, Chinese Academy of Engineering, dated June 28th 2013 (Chinese original with English translation)
F. Kriedemann, PE and Goodwin I (2003) Regulated Deficit Irrigation and Partial Rootzone Drying. Irrigation Insights 4. Land and Water Australia. Pp1-107. http://lwa.gov.au/files/products/national-program-sustainable-irrigation/pr020382/pr020382.pdf
G. Agronomy: Five crop researchers who could change the world. Nature 456: 563-568 (2008)
H. Stoll M. et al (2000) Hormonal changes induced by partial rootzone drying of irrigated grapevine. *Journal of Experimental Botany*, **51**, 1627-1634.
I See, for example, Kendrick Vineyard, California (http://www.kendricvineyards.com/); Windowrie vineyard, NSW (http://www.windowrie.com.au/); Barleystacks vineyard, SA (http://www.barleystackswines.com/about/)
J. Letter from Esporão vineyard, Portugal
K. Letter from Shiyang River Catchment Management Bureau dated 20th June, 2013 (Chinese original with English translation)
L. Tang et al. (2010) Agricultural Water Management, 97, 1527–1533
M. http://www.icid.org/ws2_2006.pdf