Institution: Lancaster University

Unit of Assessment: 7, Earth Systems and Environmental Sciences

Title of case study: 'More crop per drop': exploiting plant hormone signalling in agricultural technologies that enhance water and food security

Period when the underpinning research was undertaken: 2004 to 2014

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Ian Dodd	Professor	2001 to present
Bill Davies	Professor	1975 to 2019

Period when the claimed impact occurred: August 2013 to 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Since agriculture uses more than 70% of global fresh water supplies, more sustainable water use is vital to enhance water and food security, especially in water-scarce regions. Lancaster's research on root-to-shoot plant hormone signalling pioneered novel irrigation practices and microbial products that deliver 'more crop per drop'. The impacts of these products and practices, which are easy and inexpensive to apply, decrease crop water use (between 20% and 40%), reduce environmental degradation and restore ground-water resources. Since these products and practices also increase crop yields (up to 30%), this has boosted productivity of rural communities and improved livelihoods of smallholder farmers across China, India, Pakistan, Iran and Russia (more than 100,000 farmers in China alone).

2. Underpinning research

Research by Davies and Dodd over three decades has sought to understand how drying soil regulates crop water use efficiency (WUE, the ratio of photosynthesis to water loss through transpiration) via root-to-shoot plant hormone signalling, within the context of developing new irrigation practices and microbial products. Their REF2014 submission documented early research (between 1993 and 2002) on how drying soil enhanced production of the plant hormone abscisic acid (ABA), leading to deficit irrigation techniques that increased WUE. One form of deficit irrigation ("partial rootzone drying" = PRD), directly derived from their earlier research, has been applied across multiple crops and growing systems. PRD not only reduces water use but increased yield in 40% of examined cases compared to conventional deficit irrigation [3.4]. Realising the potential for more widespread and continued application of this technique, the researchers have sought to understand the fundamental root-to-shoot plant hormone signalling mechanisms underpinning these yield responses, leading to two conceptual advances.

Between 2004 and 2014, Davies and Dodd determined how ABA-based root-to-shoot signalling operates during PRD. Alternating wet and dry sides of the root system during PRD enhanced root-to-shoot ABA signalling compared to conventional irrigation [3.2]. Recognition that PRD and conventional irrigation induce fundamental physiological differences has sustained scientific investigations into improving the sustainability of irrigation worldwide, and informed further research at Lancaster. Furthermore, Davies and Dodd showed that PRD's effects are not only attributable to ABA, but also to enhanced production of the growth-inhibiting hormone ethylene [3.1], and decreased root-to-shoot export of growth-promoting hormones called cytokinins [3.3].

Davies and Dodd appreciated that these results pointed to approaches other than deficit irrigation that could be used to sustain plant growth in drying soil to improve WUE. They realised that plant growth-promoting bacteria associated with the roots (rhizobacteria) could offer a practical approach to attenuate the inhibitory effects of ethylene, or boost the promotive effects of cytokinins. Rhizobacteria that produce the enzyme ACC deaminase (that breaks down the

precursor of ethylene, ACC) decrease root-to-shoot ethylene signalling [3.5], while cytokinin-producing bacteria promote root-to-shoot cytokinin signalling [3.6]. They showed that these rhizobacteria could be used to alter root-to-shoot hormone signalling to enhance WUE and nutritional quality of several crops (e.g. peas, potatoes), especially those grown in drying soil [3.5], and wheat yields under rainfed cropping conditions.

3. References to the research

Novel deficit irrigation techniques to more efficiently use applied irrigation water

[3.1] Sobeih WY, **Dodd IC**, Bacon MA, Grierson D, **Davies WJ** (2004) Long-distance signals regulating stomatal conductance and leaf growth in tomato (*Lycopersicon esculentum*) plants subjected to partial rootzone drying. *Journal of Experimental Botany* 55, 2353-2363. [282 citations, Google Scholar]

[3.2] **Dodd IC**, Theobald JC, Bacon MA, **Davies WJ** (2006) Alternation of wet and dry sides during partial rootzone drying irrigation alters root-to-shoot signalling of ABA. *Functional Plant Biology* 33, 1081-1089. [106 citations, Google Scholar]

[3.3] Kudoyarova GR, Vysotskaya LB, Cherkozyanova A, **Dodd IC** (2007) Effect of partial rootzone drying on the concentration of zeatin-type cytokinins in tomato (*Lycopersicon esculentum* Mill.) xylem sap and leaves. *Journal of Experimental Botany* 58, 161-168. [179 citations, Google Scholar].

[3.4] **Dodd IC** (2009) Rhizosphere manipulations to maximise "crop per drop" during deficit irrigation. *Journal of Experimental Botany* 60, 2454-2459. [170 citations, Google Scholar]

Microbial products to sustain plant growth in drying soil

[3.5] Belimov AA, **Dodd IC**, Hontzeas N, Theobald JC, Safronova VI, **Davies WJ** (2009) Rhizosphere bacteria containing ACC deaminase increase yield of plants grown in drying soil via both local and systemic hormone signalling. *New Phytologist* 181, 413-423. [212 citations, Web of Science]

[3.6] GR Kudoyarova, AI Melentiev, EV Martynenko, LN Timergalina, TN Arkhipova, GV Shendel, LYu Kuz'mina, **IC Dodd,** SYu Veselov (2014) Cytokinin producing bacteria stimulate amino acid deposition by wheat roots. *Plant Physiology and Biochemistry* 83, 285-291. [88 citations, Google Scholar].

4. Details of the impact

Thanks to new irrigation techniques and microbial products derived from Lancaster's underpinning research, smallholders and intensive agricultural enterprises in some of the most water-scarce regions of the world have transformed their agricultural productivity and limited environmental damage due to unsustainable water extraction. Informed by the underpinning research on root-to-shoot signalling, the researchers have worked with their collaborators and partners within knowledge exchange programmes to enhance farmer uptake of specific irrigation techniques [5.1, 5.2], and developed microbial products based on root-associated bacteria.

Novel deficit irrigation techniques to more efficiently use applied irrigation water

Demonstrating the mechanisms by which PRD increases crop WUE has stimulated its global application, including in China [5.1, 5.2], the USA [5.3] and Iran [5.4]. For example, following the joint Lancaster-China Kadoorie project (from 2011 to 2013), PRD has been adopted by more than 1,200 Chinese farmers in Gansu Province alone in the form of alternate furrow irrigation (AFI) in wheat and maize crops [5.1]. In AFI, only every second furrow is irrigated on each occasion, with the irrigated furrows swapped (alternated) between successive occasions. This has decreased crop water and labour requirements, with yields between 17% and 30% greater than those obtained with conventional furrow irrigation [5.1]. Applying this technique in the Minqin Oasis has helped restore lake levels (now stable after declining historically from the 1960s to 2010) by decreasing previously excessive ground water use [5.2]. Alternative approaches (e.g. closing irrigation wells) would have decreased farmer productivity. Following application of these techniques, "*Qingtu lake, which has disappeared for more than half a century, has reappeared and formed a larger than 20 square kilometers of lake surface and more than 100 square kilometers of wetland*." [5.1]

California's processing tomato industry extensively adopted the simple AFI approach in water-scarce years such as 2016. It consistently maintained fresh yields across tomato cultivars and

environmental conditions (i.e. different seasons and soil textures) with at least 25% lower irrigation volumes than those commonly applied with conventional irrigation [5.3]. Thus, AFI remains a method of choice for many resource-poor farmers. Within California, the reduction in water use could "*keep ag land in production providing food for people, especially in drought years*" [5.3, page 5].

Scientific interactions between Lancaster / Iranian colleagues at international irrigation symposia led to changed local teaching practices in Iran and, since 2015, to local citrus farmers using AFI to manage water scarcity and improve profitability by enhancing crop quality [5.4]. One farmer notes "*the significant reduction in water consumption*" and being "*completely satisfied with this irrigation method.*" Guidance documents on the application of AFI have been published in multiple languages including Farsi by the Iranian Ministry of Agriculture [5.5, page 11 – specifically referencing Dodd's work] and Russian by the International Potato Centre.

Moreover, Chinese farmers of the most water-demanding crop – rice – now use a form of deficit irrigation by allowing flooded fields to periodically dry out, and the precise timing of drying events exploits Lancaster's understanding of how root-to-shoot signalling affects crop biomass allocation between roots, shoots and grain. While 34,000 farmers were estimated to have adopted this irrigation technique since 2014, more than 100,000 farmers in at least four provinces currently use this technique [5.6], across an approximate area of 5.4 million hectares in Jiangsu Province alone. Applying this technique has decreased water use between 23% and 42%, increased yields between 6% and 15%, and enhanced water use efficiency by 27% to 51% [5.6]. Seasonal impacts of adopting this technique are substantial, with "*economic benefits to farmers totalling approximately RMB 1728 million Yuan*" (almost GBP200 million assuming 8.65 RMB Yuan = 1 GBP) [5.6].

Microbial products to sustain plant growth in drying soil

Lancaster research demonstrated that adding specific root-associated bacteria that decrease stress-induced ethylene production [3.5] or augment plant cytokinin status [3.6] to soil can boost yields of crops grown in drying soil. While the underpinning research used single bacterial strains to test their efficacy [3.5, 3.6], companies usually supply a cocktail of different bacterial strains to deploy complementary mechanisms of plant growth promotion [5.7] to minimise the risk of inoculum failure and/or incorporate the bacteria into existing chemical fertilisers [5.8] to maximise the agronomic benefits.

Companies have developed and supplied these "biopreparations" or "biofertilisers" to farmers in India [5.7], Pakistan [5.8] and Russia [5.9], with economic gains exceeding GBP0.25 million per company per year [5.7 to 5.9]. Dryland agriculture uses these products widely and successfully, with millions of doses of ACC deaminase (the enzyme that breaks down the ethylene precursor [3.5])-containing and/or cytokinin-producing microorganisms supplied annually to farmers. The underpinning research on the relevant mechanisms of plant growth promotion captured the attention of biotechnologists throughout the world, who have isolated their own (locally adapted) microorganisms to develop specific products. Some companies' quality control procedures check ACC deaminase activity prior to product despatch [5.8], demonstrating the important link between the underpinning research, biofertilizer quality and agronomic impacts.

In India, Gujarat Eco Microbial Technologies produces the ACC deaminase-containing products *SHAFT NF* and *Platinum,* acknowledging that Lancaster research demonstrated that this microbial mechanism ameliorates plant drought stress responses [5.7]. Indeed "*we do believe it (ACC deaminase) contributes quite effectively……as we do NOT see similar results when we use products NOT containing the bacteria*". Sales and use of these products reached close to 5 million and 50 million units, respectively in 2019 and 2020, with more than 20,000 hectares being inoculated annually, with yield increases ranging from 5% to 30% [5.7].

In Pakistan, the total production of the ACC deaminase-containing products *Nutraful DAP* & *Nutraful Urea* [5.8] has continued to increase since production started in 2014. Compared to conventional fertilisers, these products increase yields by 10% to 15% in cereals, 15% to 20% in potato and 25% to 30% in sugarcane. Based on current (local) market prices for these commodities and national average production levels, this delivers an additional USD82.00, USD1,100 and USD473.00 (equivalent to GBP63.00, GBP851.00 and GBP363.00) per hectare

for cereals, potato and sugarcane, respectively. This additional revenue substantially improves farmer livelihoods, as average farm income is GBP1,200 per season.

Based on joint Lancaster-Russian research (between 2003 and 2008) demonstrating that specific bacterial strains could boost wheat yields, since 2009 the company Biomedchem has supplied the cytokinin-producing products *Elena, Azolen* and *Bacispecin* to more than 50 Russian agricultural enterprises. Indeed, the company "*recommends that farmers use this strain under the continental climate conditions of our region, which is characterized by frequent drought*" [5.9]. Based on recommended application rates, more than 500,000 hectares are inoculated annually, generating yield increments in wheat of between 10% and 20%. This boosts economic yields by RUB5,000 per hectare (GBP50.00), allowing farmers to generate 25% more income based on current wheat prices.

Looking forward, these diverse, sustained and international impacts arising from Dodd and Davies' research have further potential for continued development to reach different types of farmers throughout the world via ongoing projects:

- GCRF RECIRCULATE project *Driving eco-innovation in Africa: capacity-building for a safe circular water economy* (2017 to 2021) that is introducing deficit irrigation techniques to the researchers' collaborating partners CSIR, Ministry of Agriculture extension officers and smallholder farmers in Ghana, to assess their impacts on rural communities
- EU SHui project *Managing water scarcity in European and Chinese cropping systems* (2018-2022) that is working with new Chinese partners to better understand the socio-economics of farmer decisions to adopt these irrigation practices
- ERDF funded research (2017 to 2021) investigating cytokinin augmentation of existing microbial inoculants of legume crops in South America

5. Sources to corroborate the impact

5.1 Letter from China Agricultural University, dated 14th September 2020. Corroborates impact of application of joint research in China.

5.2 Xian Xue, Jie Liao, Youtian Hsing, Cuihua Huang, Famin Liu (2015) Policies, land use, and water resource management in an arid oasis ecosystem. *Environmental Management* 55, 1036-1051. Corroborates the impact of applying AFI in restoring Minqin Oasis lake levels.

5.3 Report from Western SARE (Sustainable Agriculture and Education) "Boosting Agricultural production through Water Use Efficiency" dated 2015. Shows impact of application of AFI on California's tomato industry.

5.4 Citrus farmer, Moghrikola village, Amirkola Ring Road, Babolsar city, Mazandaran Province, Iran. Dated 25 November 2020. Corroborates impact of applying PRD in managing water scarcity and improving profitability by enhancing crop quality. In Farsi with English translation.

5.5 Guidance document on the application of AFI produced by the Iranian Ministry of Agriculture (2020) referencing Dodd's research on page 11. In Farsi.

5.6 Letter from Yangzhou University, dated 20th April 2020. Corroborates impact of the research on farmers in Jiangsu Province.

5.7 Letter from the CEO of Gujarat Eco Microbial Technologies Pte Ltd, dated 27th November 2020. Corroborates impact of the microbial products in India.

5.8 Website of Jaffer Agro Services (2020) showing the continued production of the ACC deaminase-containing products *Nutraful DAP* & *Nutraful Urea* in Pakistan.

5.9 Letter from Research and Development Manager of NPP (Research and Production Enterprise) Biomedchem, Ufa, Russia, dated 22 April 2020. Corroborates impact of microbial products in increasing yields in Russia.