

RESEARCH ARTICLE

Healthy soils for sustainable food production and environmental quality

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Abstract Soil is the foundation for sustainable food production and environmental protection. Created by unsustainable land management practices and a range of social, economic and environmental drivers, soil degradation and pollution have been an ongoing threat to international food security and environmental quality. Soil degradation and pollution assessments are, however, often focused on the soil itself with little scope to devise new soil management approaches that match food production systems and/or environmental protection. This study draws lessons from an Australia-China Joint Research Center Program, Healthy Soils for Sustainable Food Production and Environmental Quality: a research platform that has brought together multi-disciplinary approaches from world-renowned universities and research organizations in Australia and China. To this end, a framework is presented for future soil management in a new way that combines excellence in research, industry and policymakers in a partnership that will ensure not only the right focus of the research but also that high-quality outputs will be transferable to industry and end-users.

Keywords Australia, China, environmental quality, food

production, healthy soils

1 Introduction

Soil is the foundation for sustainable agricultural development but it is a nonrenewable finite resource^[1,2]. The degradation and loss of soil are arguably one of the major ongoing threats to international food security^[3,4]. Loss of soil is created by unsustainable land management practices and a range of social, economic and environmental drivers that lead to conflicts in land use^[5]. However, there is little scope to expand the global agricultural area without major ecological, social and economic costs to food production. The conservation of high-value soil resources is vital, considering that the loss of soil resources is not recoverable within a human lifespan. This means that a new approach to the sustainable management of soils as an integral part of the food supply chain is required. Furthermore, current practices and business-as-usual approaches to agricultural and food production will not meet the estimated 60% increase in demand for food, feed and fiber by 2050^[6].

From an international viewpoint, in the last ten years there has been considerable investment in research, development and adoption of new technologies and management practices focused on soil and soil ecosystems. For instance, the Australian government has funded large scale collaborative research, development and demonstration

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projects in the National Soil Carbon Research Program between 2012 and 2017 (Climate Change Research Program) to understand soil carbon processes and the ability of Australian soils to sequester carbon thereby leading to greater resilience under future climate change scenarios. In China, the central government has invested a total arrangement of 217.22 billion CNY to implement a series of ecological construction projects, which greatly contribute to the western region's ecological protection and restoration and have made much progress in combating the processes of desertification and soil erosion^[7]. In 2016, the University of Melbourne (UM), in conjunction with the University of Western Australia, the University of Sydney, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), China Agricultural University (CAU), Nanjing Agricultural University (NAU), the Chinese Academy of Sciences (CAS), the Chinese Academy of Agricultural Sciences (CAAS), Incitec Pivot Fertilisers (Melbourne, Victoria, Australia) and Xinyang-feng Fertilizer Co., Ltd. (Jingzhou, Hubei, China), received more than 3 million AUD funding for an Australia-China Joint Research Center (ACJRC), focused on soil management systems and the impact on sustainable food production and environmental quality. Similar to the Cooperative Research Centers (CRC) Program in Australia, which is a large (50 million to 100 million AUD) cooperative research partnership between the government, industries and research providers, the ACJRC scheme is a mini international CRC, a cooperative research platform between two governments, research partners and industries to address the common challenges in soil health and sustainable farming systems.

In many ways the situation in China is similar to that in Australia when considering the challenges of soil degradation and potential loss of crop production^[8,9]. Both countries need to increase agricultural productivity by recognizing the value of the soil resource, increasing the resilience of soil to external threats, and integrating soil management into the supply chain for long-term sustainable food, fiber and freshwater. China must produce more food for its growing population from finite land resources without further degrading soil and water resources, while Australia is experiencing increasing soil losses, soil degradation and growing evidence of yield gaps due in part to inefficiencies in nutrient and water use driven by poor management practices^[10].

To tackle this task the ACJRC Program, Healthy Soils for Sustainable Food Production and Environmental Quality, had five deliverables underpinned by a core objective of delivering new research and innovative products that addressed the current and future challenges of food security and sustainable soil management. These deliverables were aligned with Australia's National Research Priorities (managing our food and water assets and lifting productivity and economic growth)^[11] and the priorities of the National Soil Research Development and

Extension Strategy. Securing Australia's soil for profitable industries and healthy landscapes^[12]. Five deliverables were identified (Fig. 1).

Deliverable 1: improve nutrient management technologies in crop and livestock systems including developing the next generation of enhanced efficiency fertilizers (EEF), improvements in techniques for measuring plant nutrient and water requirements, new precision agriculture technologies, and remote sensing technologies for increased crop, pasture and animal productivity.

Deliverable 2: increase the economic and environmental sustainability of agriculture by advancing the use of agricultural wastes, co-products and byproducts through connecting business with existing and new knowledge.

Deliverable 3: identify criteria to decide the actual and potential trade-offs between the long-term maintenance of soil resources and the requirements for short-term agricultural production, as well as barriers to, and processes for, remediation of degraded soils.

Deliverable 4: demonstrate to business and society the critical role of soils in the food supply chain by developing robust benchmarks to demonstrate sustainable (clean and green) food production.

Deliverable 5: integrate Deliverables 1 to 4 and deliver to business and other stakeholders through knowledge exchange.

The ACJRC brought together an internationally recognized research team from world-renowned universities and research organizations in Australia and China, industry leaders and national decision-makers. This interactive network provided a long-term legacy of the ACJRC by taking a holistic view on healthy soils, in a new way that combines excellence in research, policymakers and industry in a partnership that will ensure not only the right focus of the research but also that high-quality outputs will be transferable to industry and end-users (Fig. 2).

2 Significance and task orientation of the ACJRC

During the development stage of the ACJRC, several reviews were undertaken to ensure that the deliverables and the proposed outcomes from the research undertaken were aligned with existing and emerging knowledge. It was clear that the research platform would have to tackle a global problem; the ability to maintain or *create* healthy soils that are resilient and sustainable from a long-term perspective. This would have to be done using a holistic view on healthy soils and an innovative approach to bring together excellence in research, policy and industry need in a partnership that would ensure that the research focus was clear and outputs could be readily translated into products for the agricultural industries and end-users. Examples of significant opportunities for gains in farm profitability to be



Australia-China Joint Research Centre (ACJRC)
Health Soils for Sustainable Food Production and Environmental Quality

OBJECTIVES	AUSTRALIA	AUSTRALIA & CHINA	CHINA	SOLUTIONS & OUTCOMES
Efficient use of inputs and resources	<ul style="list-style-type: none"> Adoption of technologies 	<ul style="list-style-type: none"> Nutrient losses Costs of technologies 	<ul style="list-style-type: none"> Acceptance of technologies 	<ul style="list-style-type: none"> New effective fertilizer (metal-phenolic network (MPN) coatings and inhibitors) New technologies Decision support tools (GIS-based apps)
Recovery of resources from agricultural wastes	<ul style="list-style-type: none"> Few effective products 	<ul style="list-style-type: none"> Regulatory environment (social acceptance) Few product manufacturers 	<ul style="list-style-type: none"> Effective products 	<ul style="list-style-type: none"> Improved regulation New technologies (lignite amendment of feedlot manure and poultry litter; recycling dead livestock and abattoir waste) New effective fertiliser (plant-sourced organic fertilizers, bioorganic fertilizers, amendments and green manures)
Building soil sustainability and resilience	<ul style="list-style-type: none"> Land degradation Soil acidification, salinity, sodicity Low organic matter soils 	<ul style="list-style-type: none"> Subsoil constraints Climate variability 	<ul style="list-style-type: none"> Increased pressure of growing population Soil acidification and localized sodicity 	<ul style="list-style-type: none"> Reductions in soil losses Reductions in subsoil constraints Improved simulation of soil response to climate change
Avoid soil degradation and fertility decline	<ul style="list-style-type: none"> Reliance on existing best management practice 	<ul style="list-style-type: none"> Lack of new products (e.g., for soil/water/nutrient loss and contamination) 	<ul style="list-style-type: none"> Significant soil pollution and contamination with few remediation technologies 	<ul style="list-style-type: none"> New remediation technologies (SoilChip-XPS) Reduced contamination of food supply chain Extension of best management practice to farmers
Improved food credentials	<ul style="list-style-type: none"> No premium on foods that demonstrate high quality Ineffective regulation 		<ul style="list-style-type: none"> Supply chain contamination issues Food safety 	<ul style="list-style-type: none"> Improved food credentials (evidence-based footprints) Benchmarking and provenance indices New regulatory environment

Fig. 1 Key challenges, objectives and solutions for Australian and Chinese agriculture to increase soil productivity and resilience.



Fig. 2 An interactive network based on Australia-China Joint Research Center (ACJRC).

achieved through the work of the ACJRC were identified as follows.

(1) China uses about one-third of the global nitrogen fertilizer to support 19% of the world's population^[13]. Excessive use of nitrogen has led to changes in Chinese agricultural policies (The National Zero-Growth Action Plan for Chemical Fertilizer Use) that could reduce use by 20% by 2020^[14]. This target was demonstrated as feasible without reducing the grain yield by researchers from UM and CAS/CAAS in a collaborative project in north China. The research undertaken developed a decision support tool for fertilizer management which led to around a 20% reduction in nitrogen fertilizer use, amounting to a net benefit of 216 million AUD (present value) in the demonstration area [progressive benefit-cost analysis (pBCA) of 10:1] and an 7 billion AUD saving to Chinese farmers annually if implemented nationally. Further gains could be made by using new EEF (amounting to 10%–20% and could lead 2 billion to 3 billion AUD savings) if utilized by Australian and Chinese farmers (assuming at 10% adoption of the technology). The ACJRC would lead the further development and refinement of new decision support tools to assist farmers to select and use new EEF.

(2) In Australia, based on research outcomes between 2000 and 2010 it was estimated that the use of new EEF could lead to savings of more than 180 million AUD annually while also protecting the environment, by enabling reduced inputs of nutrients. While significant gains were proposed, the development of new technologies lagged industry needs. The ACJRC was tasked to reduce the variability of nutrient release from these products while increasing the certainty in yield response from EEF. This task considered not only the chemistry of new EEF but also the use of precision agriculture technologies (variable spreading, crop canopy monitoring and improvements in water management) to yield further economic and environmental benefits.

(3) In Australia, current annual estimates of the loss of production from soil-induced stresses (waterlogging, acidity, sodicity, salinity, alkalinity and elemental toxicities) approach 3 billion AUD per year (GRDC, 2013). In China, there is less detail of the economic impacts of soil degradation but in the case of soil acidity the loss of production is valued at over 12 billion AUD per year (Chinese Ministry of Environment). Even though the pBCA of soil remediation and protection of soils is relatively low (about 2 to 4:1) the long-term investment returns in research are greater than 4:1, even with low rates of adoption (10%–15%). This highlights the significant economic and environmental gains that can be achieved through new approaches to soil management.

(4) The reuse of agricultural waste products was a core objective of the ACJRC. Recent research at the UM has identified that lignite application to manures can reduce ammonia losses from intensive feedlots by 65%, with a

retained N nutrient value of 40 million AUD per year. The long-term benefits on soil security of using these nutrient-rich waste products are high (through increased organic matter additions and reduced reliance on synthetic fertilizers).

These four examples provide a framework that the ACJRC operated and facilitated strong collaboration in several key areas that are essential to achieving the goals of sustainable soil management, closing the yield gap, ensuring high-quality food with demonstrable credentials and increasing the profitability of agribusiness through research-driven innovations. Through collaboration between institutions, initially in China and Australia, and subsequently elsewhere, the ACJRC brokered knowledge and innovation to assist farmers to improve the profitability of their agricultural systems through sustainable soil management.

3 Outcomes and lessons

With the training, bilateral meeting and other research activities both in Australia and China, major outcomes in the research themes have been achieved by the ACJRC during the period 2016–2019.

3.1 Outcome 1: synchronization of nutrients and water resources

A key aspect of soil function is physical, chemical and biological processes that determine rates of release of fertilizers, growth of plant roots, soil microbial activity, and water availability. EEF have been used successfully to increase crop productivity and nutrient use efficiency in a range of crop and pasture systems^[15,16]. To establish efficient use of nutrients and water (synchronicity) for productive and sustainable agriculture, the next generation of EEFs using advanced materials coatings and inhibitors that modify the rates of nutrient release to the soil is warranted.

Using a co-design approach, the ACJRC developed a new class of fertilizers with metal-phenolic network (MPN) coatings to deliver controlled release of nitrogen for agricultural systems with managed soil water, short growing seasons and changing ontogenetic plant demand, building on the proven concept of *smart* coated fertilizers made by liquid marble technologies for dryland grain production^[17]. MPNs provide a low-cost, efficient, highly flexible and environmentally responsible method by which to coat and provide targeted nutrient release patterns to the soil environment. These supramolecular coordination structures consist of metal ions and naturally occurring polyphenols that self-assemble as films or coatings under suitable synthesis conditions^[18,19]. These systems have attracted widespread attention due to their diverse and

desirable properties such as tailorable permeability^[20], and high mechanical^[21] and thermal^[22] stability and stimuli-responsive disassembly^[21]. These properties are designed via polyphenol (e.g., tannic acid, gallic acid, epigallocatechin gallate, pyrogallol) and metal [e.g., Fe(III), Cu(II), Al(III)] selection, synthesis conditions and the physical coating process selected, i.e., layer-by-layer assembly (cyclic, alternating deposition of polyphenols and metal ions), spray-coating^[23] or electro triggered assembly^[19], respectively.

Here, inhibitors are chemical compounds designed to inhibit the conversion of urea to ammonia by the soil microbial enzyme urease (urease inhibitors), and the microbial autotrophic oxidation of ammonium to nitrite and nitrate (nitrification inhibitors). Only one effective urease inhibitor, *N*-(*n*-butyl) thiophosphoric triamide with a short half-life in soils, and three nitrification inhibitors (3,4-dimethylpyrazole phosphate, nitrapyrin, dicyandiamide) are available globally. The performance of commercially available inhibitors is highly variable, with efficacies lasting between days and weeks^[24], for reasons still poorly understood, particularly in Australian soils^[25]. The development of next generation inhibitors involved the design and synthesis of new compounds, testing of performance through *in vitro* soil incubation studies and examining their stability through tracing in soils and decomposition studies.

The research conducted by the ACJRC is at the point of commercialization. Using a range of state-of-the-art analytical techniques available at the UM, the ACJRC quantified nutrients loss and efficiencies of new products with field trials in collaboration with commercial service providers and other end-users, in landscapes of varying degrees of soil degradation. These trials include measurements of (1) growth and nitrogen contents of biomass at key growth stages including the final yield, (2) nitrogen loss pathways including ammonia (NH₃) volatilization (measured using micrometeorological techniques, e.g., open-path lasers, open-path FTIR^[26]), nitrous oxide (N₂O) emissions (measured by static chambers, open-path FTIR and quantum cascade laser^[27]), and nitrate leaching (based on mineral nitrogen dynamics and process-based modeling, e.g., water and nitrogen management model (WNMM)^[28]), and (3) fertilizer nitrogen recovery using ¹⁵N techniques.

Currently there are no systems tools available for water and fertilizer use worldwide that integrate biophysical (soil and climate) and social-economic factors, and are spatially referenced (GIS-based). The ACJRC evaluated the viability and cost-effectiveness of combining current and emerging IT platforms. This research led to the delivery of new easily utilized platforms (apps, smartphones) underpinned by multiple data streams and analytics to producers to improve on-farm management, reduce costs, increase productivity and achieve improved environmental outcomes. Also, the ACJRC developed a comprehensive

and practical decision support tool that is user-friendly and accessible to farmers and advisors.

The new fertilizers and decision tools have been integrated into the Soil & Landscape Grid of Australia, the Global Soil Map and ASRIS (end-user managed by CSIRO, Australia), and Chinese farmers (Science and Technology Backyard network developed and managed by CAU, China). These technologies have a unique opportunity to increase nutrient use efficiency in grassland systems through improved spatiotemporal management of fertilizers by introducing precision agriculture technologies to pasture production systems^[29]. The smart-farm concept has integrated various off-the-shelf soil monitoring technologies (EM38 and Veris EC sensors; satellite vegetation sensing, Landsat 8 and commercial derivatives such as Trimble's Pure Pixel Vegetation Index), proximal biomass sensors (Crop Circle), GPS livestock tracking and gridded soil survey techniques, to deliver knowledge and products to producers in both China and Australia.

3.2 Outcome 2: management of agricultural wastes

Soil degradation through losses of organic matter, changes in land use or inappropriate disposal of wastes to land is a significant challenge to sustainable food production^[30]. Agricultural production systems are suboptimal in their waste management and materials currently regarded as wastes are in fact valuable co-products^[31]. Two barriers exist: (1) much of the waste sector is heavily regulated through national legislation as well as the food industry Hazard Analysis and Critical Control Point (HACCP) systems and (2) the chemical and biological stability of wastes, water content and pathogen and contaminant loadings in the waste. If a waste stream can be managed to produce stable, low moisture and pathogen-free bioproduct at a reasonable cost, the transformation of wastes to products becomes far more viable.

In Australia, the commercial exploitation of agricultural wastes is low-technology but has increasingly gained traction with producers especially in horticulture and intensive animal industries. There is considerable knowledge in China on a range of new biofertilizers and products (reflecting Chinese government policies on *circular* farming) that can be translated to Australia thereby increasing the use of wastes in agricultural and food production. The NAU has recently developed a technique to produce plant-sourced organic fertilizers. This technology is based on aerobic composting of crop residues and straws or manures covered with molecular film at an optimal C:N ratio and incubation of priming microorganisms that can survive and grow at high temperatures. The process is friendly to the environment, highly efficient, and low-cost. Further, NAU has developed successfully an approach to recycling dead livestock and abattoir waste to make amino acid blends that can be used with crop residues as the substrate to grow *Trichoderma* strains, a widely used growth-promoting

polyglycerol polyricinoleate (PGPR) used in Chinese agriculture^[32,33]. Moreover, *Trichoderma* and straw composts can be used to produce bioorganic fertilizers, which exhibit better effects in increasing crop yields than normal manure-based composts. The ACJRC has had a pivotal role in facilitating these processes.

To achieve better utilization of scarce resources (organic matter and soils) and enhance agricultural production, the ACJRC delivered improved understanding of nutrient retention in agricultural wastes that are recycled to agricultural land, including carbon sequestration and the recovery and reuse of organic particulates from water. This also provided significant and new insights into mitigation nitrogen losses of intensive agricultural wastes, evaluation of the effect of various agricultural wastes on crop production and soil health and the amendment of waste products with nutrients to provide an appropriately balanced product. For example, studies on the lignite amendment of feedlot manure and poultry litter have been completed to explore the mechanisms of nitrogen retention, effects on dynamics of composting and impacts on soil health and plant yield in Australia. Lignite addition significantly increased the composting temperature and resulted in faster degradation of organic compounds during composting and dramatically reduced NH₃ volatilization by two-thirds^[34].

Further, bioorganic fertilizers, amendments and green manures were identified as effective management strategies to suppress soilborne pathogens. The technology patented by NAU was examined in Australia by the ACJRC for its effectiveness and mechanisms of the beneficial microbes in the bioorganic fertilizers to suppress soilborne diseases in China, such as bacterial wilt disease of tomato^[35] and tobacco^[36], Fusarium wilt of banana^[37], cucumber^[38], watermelon^[39] and vanilla^[40], and rhizome rot in ginger^[41]. It is thought that the bioactive mechanism is direct suppression of the pathogen in soil and an indirect inducement of soil suppressiveness against pathogens by manipulating the soil microbiome^[42,43]. ACJRC screened a range of specific beneficial rhizosphere microbes that can promote plant growth and suppress soilborne pathogens in Australia, and prepared composts by following standard maturation processes and inoculating with beneficial microbes. The research focused on the control of lettuce anthracnose (*Microdochium panattonianum*) using secondary metabolites from *Trichoderma* fungi delivered by first screening different strains of *Trichoderma* spp. for their capacity to produce secondary metabolites that reduce the growth of *M. panattonianum* *in vitro*. Further work on optimization of solid and liquid fermentation systems was undertaken to identify the most efficient method to produce secondary metabolites from strains previously selected. This phase of development of the fungal antagonistic system was supported by pot and field evaluations to determine their efficacy to control lettuce anthracnose.

3.3 Outcome 3: remediation and rehabilitation of degraded soils

Australia and China both face problems of soil degradation and subsoil constraints that affect soil fertility, soil health and ultimately agricultural productivity^[44,45]. China is facing serious soil pollution, particularly metal pollution, which threatens the production of safe food and may lead to population health risks and economic loss^[46]. New products developed by the ACJRC are under evaluation to mitigate the impact of a range of contaminants by refining degradable ion exchange materials (e.g., chitosan) that can absorb and release nutrients with changing soil water content. These materials can also be used as metal stabilization technologies and platforms to deploy novel microbial strategies to reduce hydrocarbon pollution. Cooperative research has identified key soil processes and mechanisms that lead to subsoil constraints in intensively cropped land, and has developed practical and economic measures to overcome decreased agricultural productivity and profitability resulting from remediating soils that have become degraded. For example, to tackle the task of remediation of Cd-contaminated paddy soils in China, a new methodology for process analyses on soil chemistry and biochemistry (SoilChip-XPS: elemental and bioprocess analyses *in situ* soil microinterfaces) was developed^[47]. The deployment of this technology has allowed new approaches to reduce Cd contents in rice (grain) and a new technique for the safe use of Cd-contaminated paddy soils to be developed^[48,49]. With these new technologies and management strategies, a more robust risk analysis approach has been developed to predict contaminant impact on the food supply chain (e.g., for the metalloid arsenic and the metals mercury, cadmium and copper) and verification of the effectiveness of different technologies and management to sequester or mitigate potential contaminants.

3.4 Outcome 4: food credentials and knowledge exchange

A wide range of indices have been proposed to assess the intricacies of soil quality, which were mostly focused on soils themselves (e.g., soil physics, biochemicals and microbes) with little scope to match food production systems and/or environmental protection^[50–52]. There is also a range of regulatory frameworks, codes of practice, accreditation schemes, environmental legislation, performance indicators and operational guidelines that underpin food credentials^[53,54]. To link soil health/quality with food credentials and contribute knowledge exchange for multiple agricultural stakeholders, a new framework with formal processes to underpin the raft of information and data has been developed by the ACJRC to generate new benchmarks for agricultural products through the production of evidence-based footprints.

There is an intuitive view that Australia produces food that is clean and green while less assurance for Chinese products, but at present this impression is neither meaningful nor readily verified^[55]. Supported by the ACJRC, 22 *in situ* monitoring sites in 11 typical agricultural regions in China have been established to monitor standards and to construct the database for greenhouse gas emissions from Chinese farmland. This work by ACJRC has contributed to an update of the N₂O direct emission factors for crops/vegetables (0.40%±0.05%), greenhouse vegetables (0.82%±0.07%) and potatoes (0.41%±0.02%). The database has assisted in evaluating new indicators by using emission intensities of greenhouse gases per net economic benefit thereby determining the effectiveness of management practices in China^[56]. By introducing the process-oriented model (denitrification-decomposition, DNDC) to the framework of reactive nitrogen spatial intensity (NrSI), a comprehensive spatial and cropwise assessment of reactive nitrogen losses has been conducted in the Bohai Rim Region, which can be used to identify the hotspots of reactive nitrogen losses at the county level for various cropping systems to set priorities of mitigation and further develop better strategies for sustainable crop production at the county level in China.

This work is of interest to all partners in the agricultural and food supply chains and will be informed through active engagement with the Sustainable Agriculture Initiative (SAI) Platform (retail and supply chain partners) as well as growers. A knowledge and innovation exchange platform is also being built to integrate outputs from individual research to assist end-users to identify both shelf-ready and emerging technologies demonstrated by the ACJRC. Ultimately, the research output, new product development (and commercialization), the adoption rate of new technologies and acceptance of new food credentials by the agricultural and food industries are all being estimated to support food products and demonstrate sustainability.

4 Commercialization of research outcomes and legacy of the ACJRC

The knowledge and innovation exchange platform has been developed to facilitate the delivery of key information between stakeholders and businesses and investors for the successful commercialization of a range of sustainable Australian products. This platform is underpinned by the systematic evaluation of novel ideas (ex-ante BCA) and assists with the development of business cases for investment, including identifying potential partners and opportunities for investment through a range of arrangements (direct investment, joint ventures, company spin-off/feasibility of start-ups). For example, the successful development and commercialization of new EEFs from Australian research might generate 0.65 billion to 1.4

billion AUD in Australian and Chinese markets, based on 10%–20% reduction in nitrogen fertilizer use and 10% adoption rate, with an estimated value (including IP and licensing) to Australian manufacturing of over 0.5 billion AUD. New precision agriculture technologies are estimated to provide more than 140 million AUD in savings and over 100 million AUD to Australian providers for new decision support tools. The increased nitrogen retained in compost products from Australian feedlots have been valued^[34] at 23 million to 64 million AUD per annum when the practice is adopted nation-wide. In addition, it will result in 1.3 million to 3.5 million AUD carbon credit based on IPCC's default emission factor of 1% redeposited ammoniacal nitrogen will be lost as N₂O and current carbon price of 14 AUD·t⁻¹ CO₂ equivalent. The economic benefit will increase considerably when these technologies are adopted by other intensive animal production industries such as poultry and pig production. New soil remediation technologies have the potential to yield more than 350 million AUD in new commercial products or licensed IP, including new degradable polymers that may be commercialized by the chemical manufacturers. The Chinese government annually invests about 15 billion AUD to remediate metal(loid)-polluted soils. There is also considerable interest in building food credentials for export markets in Australia and China. Enhanced food credentials and benchmarking/labeling clean and green for Australian products will potentially yield over 10% increase in export value annually (more than 3 billion AUD in premium market value). Adoption of new benchmarking standards through the whole supply chain is envisaged with key end-users being producers, export agencies and retailers.

5 Concluding remarks

The success of the ACJRC Program, Healthy Soils for Sustainable Food Production and Environmental Quality, has resulted in several new and emerging commercial products that can be adopted by the agricultural industries. The ACJRC has developed an approach that facilitates and combines excellence in research, policy development and industry in a partnership that will ensure that the focus of the agricultural research and high-quality outputs are readily transferable to industry and end-users. The research outcomes from the ACJRC can be used to strengthen the competitiveness of both the Australian and Chinese agricultural sectors. The research conducted provides options for remediating soils that have existing contaminant burdens, facilitate better management of soils using integrated and user-friendly decision support tools and increase farming productivity and food quality by use of customized fertilizers (EEF, biofertilizers). From an economic and environmental point of view, the research from the ACJRC provides greater benefits from reuse of wastes, reduction of yield gaps, delivery of high-value and

high-quality products and provision of broad social implications for food security and sustainability of rural communities.

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