An Roinn Talmhaíochta,
Bia agus Mara
Department of Agriculture,
Food and the Marine

Food Institutional Research Measure
Research Stimulus Fund

Final Report

Strategies for controlling cadmium contamination in Irish Food Production
RED-Cd-IRL

DAFM Project Reference No: 11SF308-

Start date: 01/11/2012
End Date: 1/10/17
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Collaborating Research Institutions and Researchers:
DAFM: Sheila Nolan, Barry Delaney, Deirdre Fay, Gabriel Roe.
University College Cork Prof. Peter Jones
University College Dublin Prof. Simon More
Please place *one* "x" below in the appropriate area on the research continuum where you feel this project fits

Basic/Fundamental → Applied → Pre Commercial

1	2	3	4	5	6x	7

Please specify priority area(s) of research this project relates to from the National Prioritisation Research Exercise* (NRPE) report;

Priority Area (s)	Food for Health Smart and Sustainable Food Production and Processing

Key words: *(max 4)* Cadmium, Horticultural Mitigation Strategies

1. Rationale for Undertaking the Research

The soil Geochemical Atlas of Ireland (Fay et al., 2007), identified that certain horticultural production areas in Ireland contained elevated cadmium levels in soil while official monitoring programmes highlighted the potential for some produce from these regions to exceed the legislative maximum levels (MLs). In 2009 the European Commission (in response to the EFSA CONTAM Panel Scientific opinion) recommended a decrease in Maximum Levels in foodstuffs. However following discussions the Commission concluded an immediate reduction would be difficult to achieve. The Commission recommended progressive implementation of known mitigation strategies, continual reporting and research to fill knowledge gaps, for certain crops or geographical regions.

The above developments, together with the results of the first Total Diet Study in Ireland (FSAI, 2012) triggered several research activities in Ireland, including this project which was conceived to find solutions to safeguard horticultural and crop production in Ireland.

2. Research Approach

The project sought to achieve the following goals

- *Develop national expertise, knowledge, and research capacity in the area of heavy metal occurrence and exposure, which can contribute to policy*
- *Characterise soil parameters that control cadmium availability for plant uptake*
- *Understand the cadmium uptake mechanism and cadmium partitioning dynamics in potatoes*
- *Determine the relationship between soil and kidney cadmium concentrations in cattle from the area of interest*
- *Develop and validate risk indices and management strategies to guide farmers to minimize cadmium levels in potatoes and carrots*
- *Rank current horticultural crops cultivars for cadmium accumulation characteristics; ultimately providing primary producers with a risk analysis and management toolkit to avoid produce exceeding the cadmium ML*

The following experiments were conducted

Field and pot studies of different soils were conducted to determine what soil parameters control cadmium availability in Irish soils. A total of 35 diverse soils mainly from the high Cadmium region were selected for pot studies with potato and carrot. For field studies 304 paired soil /plant tissue samples were taken for potato and 144 for carrot from soils both within and outside the high cadmium area in the years 2012-2015. The total cadmium concentration in the harvested tubers and carrots was determined while soil samples were

analysed for a range of parameters. A model to predict Cadmium concentration in plant tissue for both potato and carrot was developed which relies exclusively on one selective soil extraction (0.1 M CaCl2) and the measurement of 6 different elements extracted by that reagent (Cadmium, Zn, K, Mg, Mn and P). All soil/ studies were carried out with commercially relevant model varieties.

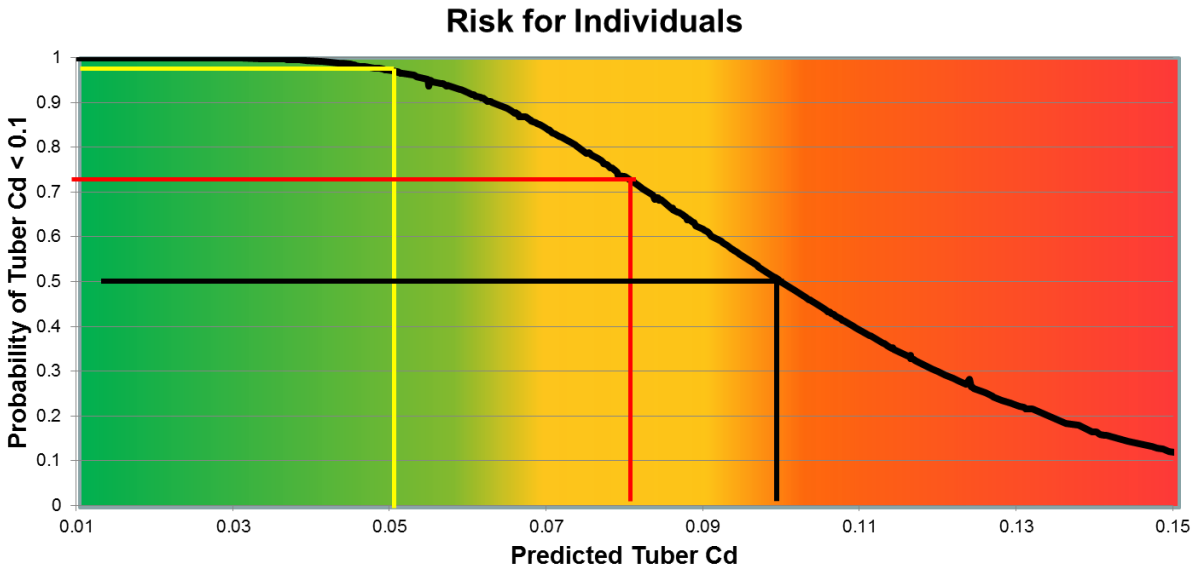
Following the screening of a range of organic and inorganic soil amendments in pot trials using potato the most promising amendments (poultry manure, farmyard manure, spent mushroom compost, brown bin waste, cattle slurry, ground limestone and burnt lime) were tested in two field trial sites with a known high cadmium uptake potential over two years.

Cultivar uptake potential for cadmium was also tested in the same field trial sites over four years for 48 potato and 28 Carrot cultivars. Salad leaf experiments were conducted under glasshouse conditions. Four common leafy salad species (watercress chard, beet, wild rocket), three spinach cultivars and two salad Brassica leaf cultivars were studied.

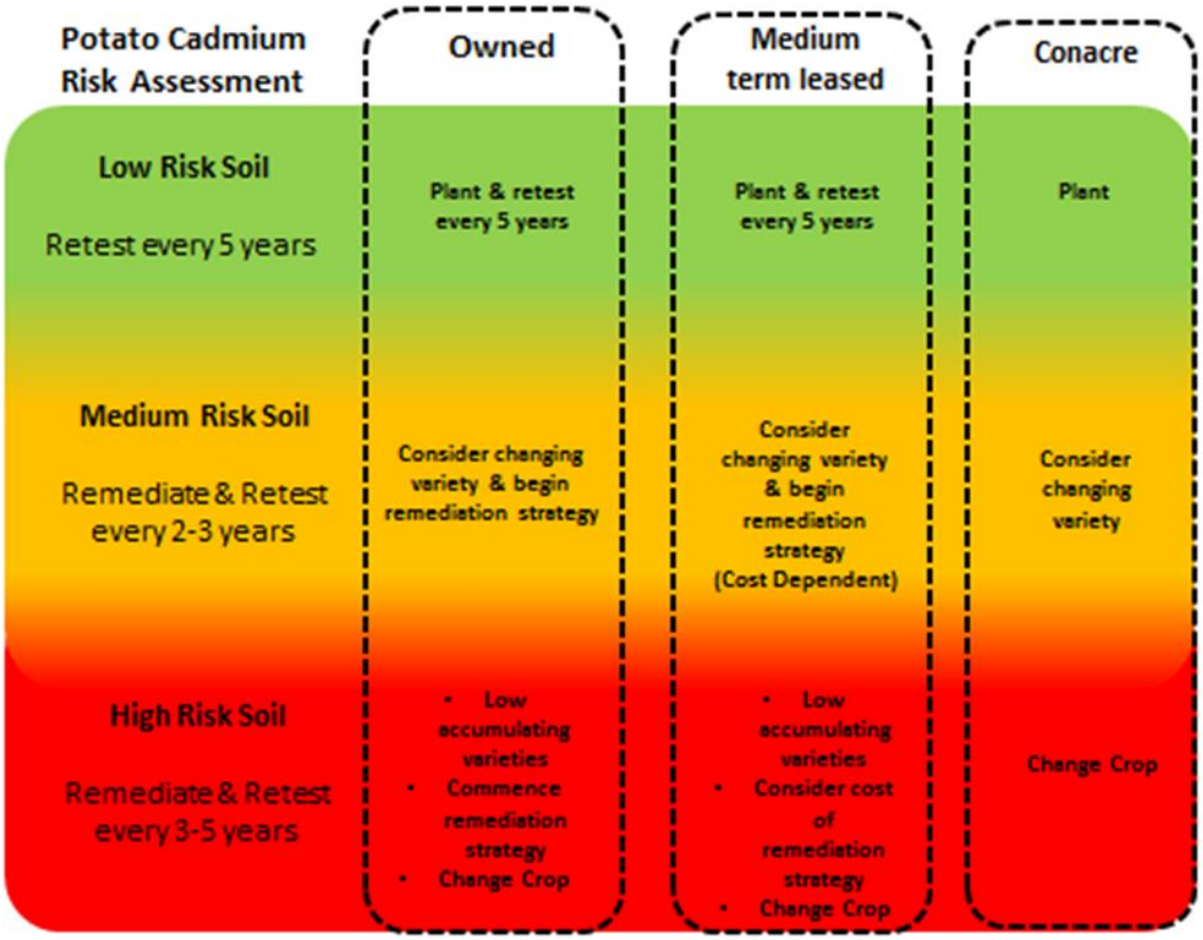
QTL mapping and physiological studies to understand Cadmium and Zinc accumulation were also carried out in potato using a cross between a high and low accumulating potato variety. The parents of this cross were used as model varieties in physiological Cadmium uptake studies.
Systematic sampling of cattle kidneys that were born and reared until slaughter in the same Irish county was conducted for kidney cadmium concentration, until a threshold number of animals from all 26 counties and 6 age categories was reached. A linear regression weighted model was developed to model kidney cadmium concentration, using the risk factors of age, sex, breed, province and estimated soil cadmium concentration.

3. Research Achievements/Results

The risk prediction model for Potato tuber cadmium exhibited a good precision with an adjusted R2 of 0.735. This model was combined with the uncertainty of prediction to develop a grower model outlining risk of a sample exceeding the ML based on the predicted tuber cadmium from soil tests (Scheme 1). A similar risk prediction model was developed for carrots. Predictions are then used with a traffic light system below to support cropping decisions (Scheme 2).



Scheme 1. *Remediation strategies for different land uses and soil risk index*



Scheme 2. Remediation strategies for different land uses and soil risk index.

Lime remediation effects on tuber cadmium content appear to be dependent on initial soil pH. Furthermore, the calcium in the lime competes with cadmium, increasing its availability and possibly delaying the effect of liming. Organic manures presented variable effects. Spent mushroom compost, poultry manure and highly decomposed farmyard manure seem to induce the highest decrease in tuber-cadmium. Application of organic manures resulted in a tuber-Cadmium reduction in the year of application and one year after application, which indicates that the effect is stable, at least over two seasons. Annual applications of lower doses will provide long-term remediation results. The capacity of different organic manures to reduce tuber cadmium concentration seems to be related to interactions between organic matter and pH, but the relationships are not clear.

Potato cultivars presented up to 5-fold differences regarding tuber-Cadmium concentration, depending on the environment (soil and climate). This suggested Cadmium accumulation is a trait suitable for selection in breeding programmes. Low accumulating varieties were also identified. Within carrots, there was less differences regarding uptake, with only a 2-fold increase across all 28 varieties tested. Most maincrop orange coloured varieties grouped together, thus a varietal choice mechanism to reduce Cd uptake was found to not be possible for carrot crops.

The salad species results showed brassica salad leaf and wild rocket are potentially lower Cadmium-accumulators compared to the other studied species. However, all of them may constitute a risk when grown in regions of high soil cadmium, with the exception of wild rocket, which always exhibited Cadmium concentrations below the ML. These data related to salad leaves needs to be validated in field experiments.

The QTL mapping experiment revealed that the region of the potato genome that plays a major role in controlling the maturity type of potato cultivars is also implicated in the genetic control of both Cadmium and Zn accumulation. In general, there was a strong correlation between early maturity and high tuber accumulation of both metals. Other genomic regions not associated with maturity were also implicated in the control of Cadmium and Zn accumulation but these had a much lower effect on the trait than the maturity locus.

The physiological time-course experiments indicated that the high accumulating variety had higher total Cadmium uptake, root-to-shoot Cadmium translocation, and greater shoot and tuber Cadmium concentration than the low accumulator. On the other hand, the low accumulator had lower uptake and higher biomass in the shoot. Grafting experiments indicated that the root system is important for total Cadmium uptake but the majority of the difference between tuber Cadmium levels was driven by foliar biomass.

Key predictors for high kidney cadmium concentration were soil cadmium, animal age and province. In areas with soils high in naturally occurring cadmium, the cadmium level in bovine kidneys can exceed the current EU ML of 1 mg/kg in older animals As a consequence, DAFM implemented a policy in Ireland to exclude kidney from selected older animals from the food chain (DAFM Trader Notice: MH 44/2014, from 19th November 2014).

4. Impact of the Research

Implementation of the project results will contribute to a lower dietary intake of Cadmium in the Irish diet while protecting the ability of growers in regions with high soil cadmium to produce crops below the relevant MLs. Results from the project were presented to the EU commission in June 2018 in collaboration with the FSAI and DAFM to inform the current debate on cadmium levels in food and seek retention of current maximum levels.

4(a) Summary of Research Outcomes

(i) Collaborative links developed during this research

Prof Mike McLaughlin from the CSIRO and University of Adelaide is a world renowned expert on Cd uptake in crops from Soil. During this project Prof McLaughlin provided advice and visited Teagasc several times where he became involved in many other soil projects. In 2019 Prof. McLaughlin became an adjunct Senior Fellow in the Crops Environment and Land Use Programme, hence fostering collaboration between Teagasc and the University of Adelaide also on other areas of soil and environmental research including phosphorus.

(ii) Outcomes where new products, technologies and processes were developed and/or adopted

The development of a National Cadmium Minimisation strategy which acts at three levels

- Dissemination of information to growers and stakeholders,
- Risk assessment of soils and fields where crops are planned using the soil CaCl2 test and risk prediction model
- The CaCl2 soil test was initially commercialised in an Irish soil analysis laboratory but is now also being adopted in a UK Laboratory (that traditionally conducts significant testing for the potato and horticultural industry) at the request of industry stakeholder
- Remediation action based on the risk of Cd uptake from the soil test and risk assessment to include (Traffic light decision system shown in results)
    - plant as crops as normal
    - change variety,
    - remediate soil and test again in 2 years
    - or change crop

(iii) Outcomes with economic potential

A national strategy for Cd minimisation, based on the outcomes of the research carried out, was developed. This effectively puts in place a set of tools that the potato and carrot producers in the area of interest can avail of to reduce the presence of Cd in potatoes.

This supports the economic development of the industry while maintaining food safety standards .

(iv) Outcomes with national/ policy/social/environmental potential

The results of the project were presented to the EU Commission in 2018 in combination with data on occurrence in produce and a urinary biomarker study (by DAFM AND FSAI respectively) at the request of DAFM and the FSAI. A final report listed under publications was also submitted.
This presentation was in response to Commission Recommendation of 4 April 2014 on the reduction of the presence of cadmium in foodstuffs (2014/193/EU). The commission recommendation aims at a progressive implementation of available mitigation strategies by farmers and food business operators and focuses on the commodities for which a reduction would have a substantial beneficial effect on consumer exposure but for which a reduction of the existing maximum levels is difficult to achieve. The specific results from this project presented were to

- Provide an overview of the geochemical occurrence of cadmium in Ireland,
- Describe the outcome of research activities to date, to mitigate cadmium uptake in horticultural produce,
- Describe the outcome of research activities to develop a method to predict Cd in potatoes based on soil sampling and associated soil risk index,

Based on this information and from other member states the Commission are currently re-assessing the situation with a view to deciding about further appropriate measures including reducing MLs in food stuffs.

4 (b) Summary of Research Outputs

(i) Peer-reviewed publications, International Journal/Book chapters.

Canty, M.J., Scanlon, A., Collins, D.M., McGrath, G., Clegg, T.A., Lane, E., Sheridan, M.K., More, S.J. 2014. Cadmium and other heavy metal concentrations in bovine kidneys in the Republic of Ireland. Science of the Total Environment, 485-486, 223-231.

Lane, E.A., Canty, M.J., More, S.J. 2015. Cadmium exposure and consequence for the health and productivity of farmed ruminants. Research in Veterinary Science, 101, 132-139.

Mengist, M.F., Milbourne, D., Griffin, D., McLaughlin, M.J., Creedon, J., Jones, P.W. and Alves, S. 2017. Cadmium uptake and partitioning in potato (*Solanum tuberosum L.)* cultivars with different tuber-Cadmium concentration. *Environmental Science Pollution Research,* 24(35), 27384-27391

Mengist, M.F., Alves, S., Griffin, D., Creedon, J., McLaughlin, M.J., Jones, P.W. and Milbourne, D. 2018. Genetic mapping of quantitative trait loci for tuber-cadmium and zinc concentration in potato reveals associations with maturity and both overlapping and independent components of genetic control. *Theoretical and Applied Genetics*, 131: 929-945.

Mengist, M.F., Milbourne, D., Alves, S., McLaughlin, M.J., Jones, P.W. and Griffin, D. 2018. Roles of shoots and roots in cadmium uptake and distribution in tubers of potato (*Solanum tuberosum L*). Plant and Soil, 430: 139–149..

Mengist M.F., Byrne S.L., Griffin D., Milbourne D. 2020. A note on the early transcriptional response in leaves and root of potato plants to cadmium exposure. *Irish Journal of Agricultural and Food Research* (in press)

Mengist M.F., Milbourne D., Griffin D., McLaughlin M.J., Creedon J., Jones P.W., Alves, S. 2021. Zinc uptake and partitioning in two potato cultivars: implications for Biofortification. *Plant and Soil (*accepted)

Several more publications on the soil prediction models for potato and carrot and the use of soils amendments to minimise Cd uptake are also in preparation. A manuscript on the different responses to Cd uptake of salad leaves is also in preparation from this project.

(ii) Popular non-scientific publications and abstracts including those presented at conferences

Creedon J., Bonner P., Wall D. & Alves S. Reporting reliable data on cadmium and lead in foodstuffs. World Congress of Food Science and Technology, Dublin, Ireland, 2016.

Alves S, Wall D, Grant J, Hennessey M, Nolan S, McLaughlin MJ, Creedon J, Bonner P & Griffin D. 2017
Cadmium Remediation in Agricultural Fields for Potato Cultivation. Session 3A: sustainable soil remediation: biogeochemical foundations and innovative approaches. Goldschmidt, Paris, France, 2017.

Mengist MF, Alves S, Creedon J, Griffin D, Hackett CA, Jones P & Milbourne D. QTL Analysis for Cadmium and Zinc Accumulation in Tubers of Tetraploid Potato using SNP Dosage Data. Plant and Animal Genome, San Diego, CA, USA, 2017.

Mengist MF, Alves S, Griffin D, McLaughlin MJ & Milbourne D. Understanding the inter-related genetics and physiology of Zn and Cd accumulation in northern European cultivated potato. World Potato Congress, Cusco, Peru2018.

(iii) National Report

Alves S, Gaffney M, Grant J, Griffin D, Hennessy M, McLaughlin M, Milbourne D, More S, Nolan S, Tlustos C, and Wall D. 2018. Final report on the progress with the implementation of the COMMISSION RECOMMENDATION of 4 April 2014 on the reduction of the presence of cadmium in foodstuffs. Prepared by Teagasc, the Food Safety Authority of Ireland and the Department of Agriculture, Food and the Marine for submission to the EU Commission.

Alves S, Gaffney M, Grant J, Griffin D, Hennessy M, McLaughlin M, Milbourne D, More S, Nolan S, Tlustos C, and Wall D. 2016. Report on the progress with the implementation of the COMMISSION RECOMMENDATION of 4 April 2014 on the reduction of the presence of cadmium in foodstuffs. Prepared by Teagasc, the Food Safety Authority of Ireland and the Department of Agriculture, Food and the Marine for submission to the EU Commission.

(iv) Workshops/seminars at which results were presented

From the research results and after consultation with the relevant stakeholders a "National Strategy for Cadmium Minimisation" was developed and a plan for its dissemination was delineated. A group comprising a member of DAFM, a Teagasc researcher and Teagasc advisor presented the issue and legislation, the research done and the national strategy for Cadmium minimisation to the relevant stakeholders, namely the potato growers in the area of interest, in meetings organised by the Irish Farmers Association, Teagasc Advisory Meetings, etc. This project has resulted in the development and retention of a national expertise both within Teagasc research and knowledge transfer and other national bodies such as DAFM and FSAI. These meetings were a joint effort across many stakeholder groups and will continue in the future.

(v) Intellectual Property applications/licences/patents - None

(v) Other – None

5. Scientists trained by Project

Total Number of PhD theses: ___1_

Please include authors, institutions and titles of theses and submission dates. If not submitted please give the anticipated submission date

Mengist, Molla Fentie. 2018. Investigating the genetics and physiological basis of differences in cadmium and zinc concentrations in tubers of potato (*Solanum tuberosum L)*: implications for food safety and bio-fortification. PhD Thesis, University College Cork.

Supervisor(s): Jones, Peter W.; Milbourne, Dan; Alves, Sheila; Griffin, Denis

Total Number of Masters theses: __1__

Michel Carl, 2016. Screening of the suitability of leafy vegetables with relevance in the Irish market for reduced Cadmium accumulation. MSc Thesis, AIX Marseille Universite.

Supervisor(s): David Wall, Michael T Gaffney, Sheila Alves, Laure Malleret

This thesis was not directly funded by the project but Carl Michel conducted the work on the project as part of a research internship and achieved his master research project from it.

6. Permanent Researchers

Institution Name	Number of Permanent staff contributing to project	Total Time contribution (person years)
Teagasc	5	1.404
UCD	1	0.1
UCC	1	0.65
Total		

7. Researchers Funded by DAFM

Type of Researcher	Number	Total Time contribution (person years)
Post Doctorates/Contract Researchers	1	3.814
PhD students	1	
Masters students		
Research Technician	2	4.2
Total		

8. Involvement in Agri Food Graduate Development Programme

Name of Postgraduate / contract researcher	Names and Dates of modules attended
No	

9. Project Expenditure

Total expenditure of the project: €788,668.75

Total Award by DAFM: €797,096.00

Other sources of funding including benefit in kind and/or cash contribution(specify): €0

Breakdown of Total Expenditure

Category	Teagasc	UCC	UCD	Name Institution 4	Total
Contract staff	345476.5				
Temporary staff					
Post doctorates					
Post graduates		84412.22			
Consumables	131026.44		90		
Travel and subsistence	32939.53				
Sub total	509442.47				
Durable equipment					
Other	18225.44				
Overheads	151147.95	25323.67	27		
Total	**678155.86**	**109735.89**	**117**		**788648.75**

10. Leveraging

Many additional research questions were raised by this project. In 2018 a follow on project 17-S-254 "Cadmium and other Heavy Metals - Detection and Mitigation in Horticultural Produce, Soils and other Crops, CREDIT (Cadmium: Reduce, Evaluate, Detect, Inform with Technologies) was funded BY DAFM. The ongoing research programmes is outlined below in Section 11 future strategies. In Addition to this project Teagasc contributed a Walsh Scholar to work in this area investigating "Understanding the fundamental kinetics of Cd uptake in soils and the amelioration mechanism of selected

amendments" in collaboration with the Soil Chemistry and Soil Quality Research Group at Wageningen University and Research

This follow on research is supporting Commission Recommendation of 4 April 2014 on the reduction of the presence of cadmium in foodstuffs (2014/193/EU) which states "Member States should ensure that where further knowledge is needed to identify the appropriate mitigation measures, e.g. for a certain crop or in a specific geographical area, investigations/research is carried out to fill these gaps in knowledge".

11. Future Strategies

1. Understanding the complex combination of soil and crop risk factors that influence availability and uptake of Cd

a. Validate and optimise soil and crop variety risk criteria for horticultural crops (Field vegetables, particularly brassicas) and oats

2. Understand soil amendment strategies

a. Validate the ability of the soil risk assessment models to prescribe amendments

b. Evaluate new amendments

c. Identify synergies between different amendments and also appropriate application rates

d. Evaluate longer term remediation of land through incremental amendment applications

3. Development of a practical and reliable toolkit for Cd detection and risk prediction

a. Develop novel rapid detection systems with specific utility in Cd research: electrochemical (Lab-on-Chip) and portable laser induced breakdown spectroscopy LIBS for Cadmium and other heavy metals in soils, plants, fertilisers (organic and chemical)

b. Develop portable electrochemical (Lab-on-Chip) and LIBS systems for determining available and total Cd in soils, fertiliser and plant material

c. Apply sensors to aid fundamental understanding of soil kinetics and evaluation of amendments

d. Evaluate a range of techniques for in field risk assessment parameters (LIBS, XRF and MIR)

4. Development of user-friendly decision support tools

a. Engage farm advisors and farmers in the development of effective advisory strategies to support adoption of best practice Cd mitigation strategies at farm

b. Develop a practical, revised and expanded Cd risk assessment and management strategy to guide farmers to minimise Cd levels in produce

c. Based on the risk assessment strategy, develop a 'traffic-light' type decision support tool for use *on-farm*