



FINAL REPORT TEMPLATE

CRDC ID: ANSTO1801

Project Title: Quantifying the nitrogen cycle: from farm gate to catchments, groundwater and atmosphere

Confidential or for public release? For Public Release

Recognition of support: The Research Provider ANSTO and UNSW acknowledges the financial assistance of the Cotton Research and Development Corporation, AINSE (Australian Institute of Nuclear Science and Engineering) and Endeavour Mobily Grants (Commonwealth government), in order to undertake this project.

Part 1 – Contact Details & Submission Checklist

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Submission checklist.

Please ensure all documentation has been completed and included with this final report:

- Final report template (this document)
- Final Technical Report ([Please see Individual reports accompanying this document](#))
- Final Schedule 2: IP register
- Final Schedule 3: Acknowledgment
- Final financial report
- PDF of all journal articles (for CRDC's records) ([Please see Individual journal articles, abstracts, posters and other outputs accompanying this document](#))

Signature of Research Provider Representative:



Dr Suzanne Hollins - Head of Research

Date submitted: 01/11/2022

Part 2 - Monitoring & Evaluation

This data is for CRDC's internal M&E requirements. Please complete all fields and add additional rows into each table if required.

Achievement against milestones in the Full Research Proposal

Milestone	Achieved/ Partially Achieved/ Not Achieved	Explanation
1.1 NAMOI: <ul style="list-style-type: none"> • Consultation with NSW Office of Water, EPA and Kierran O'Keefe • Collation of regional geochemical, flow and groundwater data and first geochemical testing (surface and groundwater)-Year 1 	Achieved	Please see both surface water and groundwater (report-2 and 4) in outputs table.
1.2 NAMOI: <ul style="list-style-type: none"> • Completion of geochemical testing (surface and groundwater)-Year 2 • Event sampling, this depends on rainfall conditions. (The opportunity eventuated in February 2021). 	Achieved	(The opportunity for event sampling eventuated in February 2021)
2.1 NOGOA: <ul style="list-style-type: none"> • Collation of all abundant regional information on surface, groundwater and nutrients. • Selection of sites for spot surface and groundwater sampling- Year 2 	Achieved	Please see both surface water report (report-1) and groundwater publication (publication-1) in outputs table.
2.2 NOGOA: <ul style="list-style-type: none"> • Completion of geochemical testing (surface and groundwater)-Year 3 • Event sampling, this depends on rainfall conditions. 	Achieved	(The opportunity for event sampling eventuated in December/January 2020)
3.1 MURRUMBIDGEE: <ul style="list-style-type: none"> • Collation of regional geochemical, flow and groundwater data and first geochemical testing (surface and groundwater)-Year 2 	Achieved	Please see both surface water and groundwater reports (reports 3 and 5) in outputs table.

<ul style="list-style-type: none"> • Selection of sites for spot surface and groundwater sampling- Year 2 		
<p>3.2 MURRUMBIDGEE:</p> <ul style="list-style-type: none"> • Completion of geochemical testing (surface and groundwater)-Year 3 • Event sampling, this depends on rainfall conditions. (The opportunity eventuated in November 2021). 	Achieved	(The opportunity for event sampling eventuated in November 2021)
<p>4.1. N₂O Atmosphere</p> <ul style="list-style-type: none"> • Consultation with the Clean Energy Regulator about N₂O emissions • Bimonthly grab samples to be analysed for N₂O concentration and isotopic composition. <p>New Milestone Groundwater samples from the Nogoia, Murrumbidgee and Namoi catchments will be degassed and the collected air analysed for its N₂O concentration and isotope chemistry. These data will provide new insights to control understanding the groundwater portion of the catchment scale nitrogen cycle and its interaction with the unsaturated zone and the atmosphere.</p> <p>Old Milestone</p> <ul style="list-style-type: none"> • Namoi Catchment 1: Setup in-field instrumentation to collect longitudinal diel measurements of site-specific N₂O concentrations and isotopic ratios ($\delta^{15}\text{N}$). These aspects we not costed in the original proposal). 	New milestone: Achieved	Old Milestone was revised because work undertaken at EMPA Switzerland (Stephen Harris) demonstrated the need for the analyser to be run in a temperature-controlled environment, and for numerous calibration gases to be deployed to enable precise measurements.
<p>4.2. Nogoia N₂O/ atmosphere</p> <ul style="list-style-type: none"> • Nogoia R Catchment: Bimonthly grab samples to 	Achieved	Analysis finalised in December 2021 with interpretation finalised in

be analysed for N ₂ O concentration and isotopic composition.		April 2022. See report-6 in outputs table.
4.3 Murrumbidgee N ₂ O/ atmosphere <ul style="list-style-type: none"> Lower Murrumbidgee River Catchment: Bimonthly grab samples to be analysed for N₂O concentration and isotopic composition. 	Achieved	Analysis finalised in December 2021 with interpretation finalised in April 2022. See report-6 in outputs table.
4.4. Consolidated insights on atmospheric emissions of N ₂ O from cotton growing landscapes	Achieved	Analysis finalised in November 2021 with interpretation finalised in May 2022. See report-5 in outputs table.

Outputs produced (Please refer to examples document to assist in completing this section).

Output	Description
Report-1	<p>A summary of 18 months of surface water hydrogeochemistry and selected isotopes in the Nogoa River from Fairbairn Dam to the confluence with the Comet River. The report discusses N-compounds and catchment specific issues like variations in salinity downstream. The report includes sampling at Theresa Ck and a detailed high-flow N-compounds assessment at Theresa Ck. The N-cycle implications are framed within regional assessments of the Fitzroy River basin.</p> <p>File Name (PDF): CRDC_ANSTO1801_Nogoa Surface Water REPORT_October 2021_Output Report 1</p> <p>Reference: Cendón, D.I., Hankin, S., Harris, S., Peterson, M., Dimovski, C., and Kelly B.F.J (2021) Quantifying the N-cycle: hydrochemistry and isotopes in the Nogoa River (QLD). ANSTO/C1745 A report to the Cotton Research and Development Corporation. August 2021, 84 pp.</p>
Report-2	<p>A summary of 18 months of surface water hydrogeochemistry and selected isotopes in the Namoi River from Keepit Dam to Wee Waa including sampling further downstream along the Pian Ck anabranch. The report concentrates on N-cycle compounds and also includes sampling of major tributaries during a high-flow sampling. Special attention is given to NO₃-isotopes variations at Keepit Dam and their evolution downstream.</p> <p>File Name (PDF): CRDC_ANSTO1801_Namoi Surface Water REPORT_February 2022_Output Report 2</p> <p>Reference: Hankin, S., Cendón, D.I., Harris, S.J., Peterson, M.A., Dimovski, C., Kelly, B.F.J. (2022). Quantifying the N-cycle: hydrochemistry and isotopes in the</p>

	Namoi River. ANSTO/C1763, prepared for the Cotton Research and Development Corporation, November 2021, 95 pp.
Report-3	<p>A summary of 18 months of surface water hydrogeochemistry and selected isotopes in the Murrumbidgee River from Gundagai to Carrathool. We included sampling along major and secondary irrigation channels including Mirrool Ck in its flow downstream from Griffith. The report concentrates on N-cycle compounds and includes sampling of the Murrumbidgee River during a high-flow event. Special attention is given to NO₃-isotopes and rare earth elements and the importance of urban inputs.</p> <p>File Name (PDF): CRDC_ANSTO1801_Murrumbidgee Surface Water REPORT_May 2022_Output Report 3</p> <p>Reference: Cendón, D.I., Hankin, S., Harris, S., Peterson, M., Dimovski, C., and Kelly B.F.J (2022) Quantifying the N-cycle: hydrochemical and isotopic composition of the Murrumbidgee River (NSW). ANSTO/C1803 A report to the Cotton Research and Development Corporation. May 2022, 90 pp.</p>
Report-4	<p>This report outlines the results of shallow groundwater sampling in the Namoi River floodplain between Turrawan and Wee Waa, with particular attention to samples recovered from two cross sections perpendicular to the Namoi River (Cardale-Mollee Rd and Spring Plains) and two sections following the Namoi River (Turrawan and Kamilaroi). A comprehensive suite of hydrochemical and isotopic makers is analysed including abundant previous work in our group. Differences in N-compounds and processes at a wider scale are discussed.</p> <p>File Name (PDF): CRDC_ANSTO1801_Namoi Groundwater REPORT_July 2022_Output Report 4</p> <p>Reference: Hankin, S., Cendón, D.I., Harris, S.J., Peterson, M.A., Dimovski, C., Kelly, B.F.J. (2022). Quantifying the N-cycle: hydrochemistry and isotopes of shallow groundwater in the Lower Namoi Alluvium. ANSTO/C1808, prepared for the Cotton Research and Development Corporation, June 2022, 64 pp.</p>
Publication-1	<p>This open-source journal publication presents a detail shallow groundwater study in the Nogoia River catchment around Emerald. It concentrates in N-compounds and with the aid of novel applications like natural ³⁶Chloride isotopes constraints the fate of nitrogen compounds along groundwater flowpaths downstream from irrigated areas.</p> <p>File Name (PDF): CRDC_ANSTO1801_Nogoia Groundwater Publication_Harris et al 2022_Output Publication 1</p> <p>Reference: Harris, S.J. Cendón, D.I., Hankin, S.I., Peterson, M.A., Shuang Xiao, Kelly, B.F.J. (2022) Isotopic evidence for nitrate sources and controls on denitrification in groundwater beneath an irrigated agricultural district. Science of the Total Environment, 817, 152606. https://doi.org/10.1016/j.scitotenv.2021.152606</p>

Publication-2	<p>(not funded by CRDC but directly linked to our CRDC project)</p> <p>This open-source publication has become a fundamental reference to any research measuring N₂O with modern laser spectroscopy. The work was applied to all atmospheric samples collected within this project.</p> <p>File Name (PDF): CRDC_ANSTO1801_N2O isotopic analysis_Harris et al 2020_Output Publication 2 and CRDC_ANSTO1801_N2O isotopic analysis_Output Publication 2_Supplementary Information</p> <p>Reference: Harris, S.J., Liisberg, J., Xia, L., Wei, J., Zeyer, K., Yu, L., Barthel, M., Wolf, B., Kelly, B.F.J., Cendón, D.I., Blunier, T., Six, J. and Mohn, J. (2020) N₂O isotopocule measurements using laser spectroscopy: analyzer characterization and intercomparison. Atmos. Meas. Tech. 13, 2797-2831. https://doi.org/10.5194/amt-13-2797-2020</p>
Presentation-1	<p>Details the N₂O analysis from groundwater samples in the Namoi River alluvial aquifer.</p> <p>File Name (PDF): CRDC_ANSTO1801_Namoi N2O Groundwater Presentation_EGU2018_Output Presentation 1</p> <p>Reference: Harris S.J., Cendón D.I., Hankin S.I., Kelly B.F. (2018). Occurrence and controls on N₂O accumulation in the lower Namoi alluvial aquifer, Australia. Geophysical Research Abstracts, vol 20, EGU2018-10576 (Vienna, Austria, 8-13 April). https://meetingorganizer.copernicus.org/EGU2018/EGU2018-10576.pdf</p>
Presentation-2	<p>Presented initial findings of protocols and corrections to achieve best N₂O isotopic measurement with laser spectroscopy.</p> <p>File Name (PDF): CRDC_ANSTO1801_N2O isotope spectrometers_Harris et al Page 20_Output Presentation 2</p> <p>Reference: Harris S, Liisberg J, Wolf B, Xia L, Yu L, Wei J, Kelly B, Blunier T, Mohn J. Comparison of N₂O isotope spectrometers for high-precision measurements in ambient air and incubation experiments Arbeitsgemeinschaft Stabile Isotope - ASI 2018, Munich, Germany. Arbeitsgemeinschaft Stabile Isotope - ASI 2018. 01 Oct 2018</p>
Presentation-3	<p>Presented a comparison of different commercially available laser spectrometers for measurement of N₂O isotopes.</p> <p>Reference: Harris S, Liisberg J, Wolf B, Xia L, Yu L, Wei J, Barthel M, Kelly B.F.J., Blunier T, and Mohn J. A comparison of commercially-available quantum cascade laser spectrometers to measure N₂O isotopocules ($\delta^{15}N_{\alpha}$, $\delta^{15}N_{\beta}$ & $\delta^{18}O$) at ambient concentrations, 8th International Symposium on Non-CO₂ Greenhouse Gases, 12-14 June 2019.</p>
Presentation-4	<p>Presented work to an international scientific community on N-cycling in the shallow groundwater around Emerald (QLD).</p> <p>File Name (PDF): CRDC_ANSTO1801_N cycling in Nogoia Shallow groundwater_EGU2019_Harris et al_Output Presentation 4</p> <p>Reference: Stephen J. Harris, Dioni I. Cendón, Mark A. Peterson, Hankin I. Stuart, Jessica Watson, Shuang Xiao, Bryce F. Kelly (2019) Nitrogen cycling dynamics in a humid subtropical climate: insights from the Nogoia River sub-catchment, central</p>

	<p>Queensland, Australia. Geophysical Research Abstracts, Vol. 21, EGU2019-6249, 2019, EGU General Assembly 2019 https://meetingorganizer.copernicus.org/EGU2019/EGU2019-6249.pdf</p>
Presentation-5	<p>Presented work in an international forum on research developed to use Rare Earth Elements and Yttrium to detect anthropogenic inputs from urban inputs and fertilisers in river waters.</p> <p>File Name (PDF): CRDC_ANSTO1801_REY in river waters_Goldschmidt2019_Cendon et al_Output Presentation 5 Abstract and CRDC_ANSTO1801_REY in river waters_Goldschmidt2019_Cendon et al_Output Presentation 5 Poster</p> <p>Reference: Dioni I. Cendón, Stephen J. Harris, Bryce F. Kelly, Mark A. Peterson, Stuart I. Hankin, Brett Rowling, Jessica Watson, Shuang Xiao (2019) Fertilizers rule REYs: agricultural catchments of Eastern Australia. Goldschmidt 2019, Barcelona 18-23 August. https://apo.ansto.gov.au/dspace/bitstream/10238/12704/1/507.pdf</p>
Presentation-6	<p>Presented to an international scientific community. Detailed work developed to improve protocols to analyse N₂O isotopes.</p> <p>File Name (PDF): CRDC_ANSTO1801_N2O isotopic analysis_EGU2020_Mohn et al 2020_Output Presentation 6 Abstract and CRDC_ANSTO1801_N2O isotopic analysis_EGU2020_Mohn et al 2020_Output Presentation 6 Presentation</p> <p>Reference: Mohn, J., Rupacher, J., Moossen, H., Toyoda, S., Biasi, C., Kaiser, J., Harris, S., Liisberg, J., Wolf, B., Xia, L., Barthel, M., Yu, L., Kantnerová, K., Wei, J., Pearce, R., Webber, E. M., Kelly, B., Blunier, T., Yoshida, N., and Brewer, P. and the Additional co-authors: N2O isotope research: development of reference materials and metrological characterization of OIRS analyzers within the SIRS project, EGU General Assembly 2020, Online, 4–8 May 2020, https://doi.org/10.5194/egusphere-egu2020-18624 https://meetingorganizer.copernicus.org/EGU2020/EGU2020-18624.html</p>
Presentation-7	<p>Presented to an international community. This work was developed in the Murrumbidgee catchment using Artificial Intelligence methods to forecast groundwater levels.</p> <p>File Name (PDF): CRDC_ANSTO1801_Forecasting GW levels Murrumbidgee_EGU2020_Xiao et al_Output Presentation 7 Abstract and CRDC_ANSTO1801_Forecasting GW levels Murrumbidgee_EGU2020_Xiao et al_Output Presentation 7 Poster</p> <p>Reference: Xiao, S., Cendón, D., and Kelly, B.: Gradient Boosting for Forecasting Groundwater Levels from Sparse Data Sets in an Alluvial Aquifer Subjected to Heavy Pumping and Flooding, EGU General Assembly 2020, Online, 4–8 May 2020, https://doi.org/10.5194/egusphere-egu2020-12501, 2020 https://meetingorganizer.copernicus.org/EGU2020/EGU2020-12501.html</p>
PhD-Thesis	<p>This PhD thesis is a detailed study of the fate of nitrogen compounds in shallow groundwater of the Emerald Irrigation Area.</p> <p>File Name (PDF): CRDC_ANSTO1801_PhD Thesis HARRIS Stephen FINAL_Output PhD Thesis</p> <p>Reference: Stephen Harris (2021, UNSW, PhD awarded 25th November 2021): Isotopic evidence for the cycling of nitrate and nitrous oxide in aquifers beneath</p>

	<p>an irrigated agricultural district using established and emerging measurement techniques. PhD Thesis, UNSW Sydney, Australia.</p>
Honours-Thesis	<p>This thesis investigates the impact of dam water releases and other anthropogenic activities on water quality. Particular focus is placed on electrical conductivity, dissolved oxygen and water stable isotope data in the Lower Murrumbidgee Catchment (September 2018 - February 2020) during drought.</p> <p>File Name (PDF): CRDC_ANSTO1801_Honours Thesis Jessica Watson FINAL_Output Honours Thesis</p> <p>Reference: Watson (2020, UNSW). River regulation impacts on water quality in the Lower Murrumbidgee Catchment. Honours Thesis, UNSW Sydney, Australia.</p>
Presentation 8	<p>This poster was submitted to present growers work done in the groundwater of the Emerald district. The Australian Cotton Collective 2021 was eventually cancelled due to COVID but the poster have been sent to CRDC and used in presentations in the Emerald region in meetings with growers.</p> <p>File Name (PDF): CRDC_ANSTO1801_Emerald groundwater water_for Australian Cotton Collective 2021 v2_Output Presentation 8</p> <p>Reference: Harris, S.J., Cendón, D.I., Kelly, B.F.J., Peterson, M., Hankin, S., Shuang Xiao (2021). Groundwater nitrogen cycling in the Emerald Irrigation Area, Emerald, Queensland. 2021 Australian Cotton Collective, Toowoomba 24th – 26th August.</p>
Presentation 9	<p>This poster was submitted to show growers work done on the water quality of the Namoi River. The Australian Cotton Collective 2021 was eventually cancelled due to COVID but the poster has been sent to CRDC for distribution or use.</p> <p>File Name (PDF): CRDC_ANSTO1801_Namoi surface water_for Australian Cotton Collective 2021 v5_Output Presentation 9</p> <p>Reference: Hankin, S., Cendón, D.I., Harris, S.J., Kelly, B.F.J., Peterson, M., Shuang Xiao (2021). Nitrate and water quality in the Namoi River From Keepit Dam to the Pian Creek. 2021 Australian Cotton Collective, Toowoomba 24th – 26th August</p>
Presentation 10	<p>This poster was submitted to present growers work done in the groundwater of the Emerald district. The Australian Cotton Collective 2021 was eventually cancelled due to COVID but the poster has been sent to CRDC and used in presentations in the Emerald region in meetings with growers.</p> <p>File Name (PDF): CRDC_ANSTO1801_Emerald surface water_for Australian Cotton Collective 2021 v3_Output Presentation 10</p> <p>Reference: Cendón, D.I., Harris, S.J., Kelly, B.F.J., Peterson, M., Hankin, S., Shuang Xiao (2021). Surface water quality in the Emerald region: From Maraboon Lake to the Mackenzie River. 2021 Australian Cotton Collective, Toowoomba 24th – 26th August.</p>

Report -5	<p>This report presents and interprets nitrous oxide concentration and isotopic measurements in the three studied catchments during this project.</p> <p>File Name (PDF): CRDC_ANSTO1801_Air Samples Report_Final_04_08_2022_Output Report 5</p> <p>Reference: Harris, S.J., Kelly, B.F.J., Hankin, S., Peterson, M., Cendón, D.I. (2022). Mole fraction and isotopic measurements of nitrous oxide in tropospheric air in the Namoi, Nogoia and Murrumbidgee Catchments (2017-2020). May 2022, 22 pp.</p>
Report -6	<p>This report presents work developed from groundwater in the Lower Murrumbidgee between Narrandera and Carrathool. Unlike previous reports this report also analysed samples recovered from deeper portions of the Lower Murrumbidgee Aquifer.</p> <p>File Name (PDF): CRDC_ANSTO1801_Murrumbidgee Groundwater REPORT_v3_Output Report 6</p> <p>Reference: Harris, S.J., Cendón, D.I., Hankin, S., Peterson, M.A., Shuang Xiao, Dimovski, C., Kelly, B.F.J. (2022). Quantifying the N-cycle: hydrochemistry and isotopes of groundwater in the Lower Murrumbidgee Catchment. ANSTO/C1819, prepared for the Cotton Research and Development Corporation, September 2022, 77 pp.</p>
Publication-3	<p>This publication will be sent to CRDC ahead of publication for assessment, coinciding with this final report. The publication investigates N₂O in the groundwater of the Emerald Irrigation Area providing a detail account of processes affecting N-compounds once recharged into the local groundwater systems. N₂O production pathways, the extent to which reduction to inert N₂ occurs, and the hydrogeochemical controls on these processes is critical in identifying and mitigating potential impacts of N-enriched groundwater on atmospheric N₂O budgets in the region.</p> <p>File Name (PDF): CRDC_ANSTO1801_Attributing N2O production pathways_ Harris et al 2022_Output Publication 3</p> <p>Reference: Harris, S.J., Cendón, D.I., Barthel, M., Hankin, S., Peterson, M.A., Six, J., Kelly, B.F.J. (2023). Attributing N2O production pathways and reduction to N₂ in groundwater using an isotope mapping approach. To be submitted to Biogeosciences.</p>

Outcomes from project outputs (Refer to examples document).

Outcome	Description
Database documenting the condition of natural assets used by the industry. Water quality data in the Murrumbidgee River.	The cotton industry is often singled out for their N-compound contribution to water ways. However, a recent study by the Australian Academy of Sciences (2019) into the causes of the Jan-Feb 2019 fish kills at Menindee Lakes found that: <i>"There is insufficient information on nutrients and their sources to know whether the nitrogen, and especially phosphate, needed to promote algal blooms has</i>

	<p><i>come from fertilisers or stock.”</i> Our research shows that at low flow most of those N-compounds are already in the waterways before reaching cotton regions. However, most N-compounds are transported at high flow events, not during drought. Our research, as revealed by nitrate isotopes along the Murrumbidgee River, is consistent with soil organic nitrogen and sewage sources for the Murrumbidgee River. Samples along Mirrool Ck had sewage/manure contributions and showed increasing degradation of water quality downstream. The scarcity of water during drought and stringent land management practices within cotton farms (zero off-farm run-off policies) makes this sector a very unlikely contributor to background nutrients concentrations at times of drought. No contributions from potential groundwater running into waterways was detected in the study.</p>
<p>Database documenting the condition of groundwater assets used by the industry in the Murrumbidgee alluvial aquifers.</p>	<p>This is the first study in the region that investigates N-compounds in groundwater incorporating nitrate and N₂O isotopes. Groundwater in the region has N-compounds, derived from agriculture, mostly concentrated in the shallow groundwater systems. The large scale of the region and a long and diverse agricultural history is reflected in the diverse N-sources compatible with results obtained at different sites. For example, the detection of NO₂⁻, which was likely derived via the denitrification pathway (i.e., the reduction of NO₃⁻ to NO₂⁻), is quite unlike other catchments studied in this project and represents a part of the N-cycle not previously considered in the study area by other authors.</p>
<p>New detailed chemical and isotopic analysis of fertilisers in Australia.</p>	<p>A total of 24 commercial fertilisers were sourced from different regional distributors and analysed in detail. Analysis included different elemental and isotopic tracers used in environmental studies. Additionally, several trace elements of interest to cotton growers were also included (i.e.: Zn, Mo).</p>
<p>Database documenting the condition of surface water assets used. Namoi River at base flow.</p>	<p>Historically there has been little data collected on the chemical inputs from urban centres, industry, dryland farming and irrigated agriculture for rivers throughout catchments of interest for the cotton industry. If we are to improve the health of our waterways, we need high quality data to understand the sources of excess nutrients and other chemicals that may have a detrimental impact on riverine ecosystems. This report fills that knowledge gap for the Namoi River.</p> <p>Keepit Dam water already contains enhanced N-compounds. When this water is released during a drought, the majority of N-compounds in the river was transported</p>

	<p>from the upper Namoi (Lake Keepit or Peel River) to Wee Waa with no systematic increase in concentration across the cotton growing areas.</p> <p>During the March 2021 high flow event Trip 11, EC was diluted to less than half of pre-drought levels in all river samples and was also low in all runoff and tributary samples. All major ions are also substantially diluted compared to the regular flow periods. However, river nutrients (TDN-N and TDP-P) were elevated on average by 200% and 500% respectively during the high flow period both TDN-N and TDP-P increased progressively downstream. The highest values of TDN-N and TDP-P were in overland surface runoff.</p> <p>Dissolved NO₃ isotopes measured from river water samples during the March 2021 high flow event display a mixing trend with a diffuse N source similar to that expected from manure, increasing with distance downriver and well represented in the runoff/tributary samples. Flow during the March 2021 event originated mostly from the Peel, Mooki and Cox's Creek catchments, with comparatively little contribution from the Lake Keepit catchment as the Upper Namoi flows were captured by Keepit Dam at the time. The majority of TDN measured in the river occurred during high flow and increased downriver, the NO₃ isotope signatures suggest runoff through grazing land to be the dominant source of NO₃ transfer down the lower Namoi.</p>
<p>Database documenting the condition of groundwater assets used by the industry in the Namoi River alluvial aquifer.</p>	<p>A total of 23 groundwater sample sets were collected in October 2017 from the shallow aquifer in the Lower Namoi alluvium and over 300 individual chemical and isotopic analyses were performed. The samples were collected in 4 transects, with the Spring Plains Rd and Kamilaroi transects considered to be the most representative of conditions across the wider Lower Namoi cotton irrigation area, the Cardale-Mollee Rd transect intersecting an area affected by upwelling of GAB water and the Turrawan transect showing conditions across the end of the Upper Namoi valley.</p> <p>TDN at Spring Plains Rd was found to be higher than other transects and occurs mostly as NO₃⁻ and DON. The spatial distribution of NO₃⁻ shows correlation with land use. Low NO₃⁻ concentrations are located beneath the river floodway area and higher concentrations beneath irrigated areas.</p>
<p>Database documenting the condition of surface water assets used. The Nogoia River.</p>	<p>This dataset constitutes the most detailed hydrogeochemical information available in the Nogoia River. Up to 60 different field parameters, isotopic ratios or chemical analytes were measured for most water samples, measuring well over 1000 individual results above detection limits. Filtered total dissolved nitrogen (TDN-N) concentrations at Lake Maraboon were generally below the</p>

	<p>WQO value for TN (< 1.070 mg/L) for the Upper Nogoia River. Variations in TDN-N nutrient concentrations downstream was small with denitrification detected in some reaches. Diffuse point source inputs could be of importance as detected in Theresa Ck. In late January 2020, coinciding with a high flow event, we collected 8 samples at Theresa Creek during ~40 hours. This even sampling demonstrated most N-Compounds are transported at high flow. Yields of dissolved inorganic nitrogen (DIN=NO_x-N+ Ammonium Nitrogen) during the 3 days of high flow amount to ~0.58 kg/km². Nitrate isotopes indicate a N fertiliser origin. This database also analyses salinity variations along the Nogoia River. As an example, the electrical conductivity measured at Bridge Flats and that observed in the Mackenzie River, just downstream of the Comet River confluence, cannot be reconciled without additional elevated EC inputs between those two sites. Those additional inputs we interpret as linked to groundwater discharge with no additional agricultural tracers detected in the river (i.e. increase in N-compounds or fertiliser isotope signatures).</p>
<p>Database documenting the condition of groundwater assets used by the industry in the Emerald Irrigation Area.</p>	<p>This dataset investigates the N-compounds in the Emerald Irrigation Area - region with no groundwater usage for irrigation with all irrigation originating from Fairbairn Dam. Fertiliser-derived N is likely incorporated, and retained in, the soil organic N pool prior to its mineralisation, nitrification, and migration into aquifers. This process, alongside the near absence of other anthropogenic N sources, results in a homogenised groundwater NO₃⁻ isotopic signature that allows for denitrification trends to be distinguished. Regional-scale denitrification manifests as groundwater becomes increasingly anaerobic during flow from the upgradient basalt aquifer to the downgradient alluvial aquifer. Dilution and denitrification occur in localised electron donor-rich suboxic hyporheic zones beneath leaking irrigation channels. Using approximated isotope enrichment factors, estimates of regional-scale NO₃⁻ removal ranges from 22 to 93% (average: 63%), and from 57 to 91% (average: 79%) beneath leaking irrigation channels.</p>
<p>Database of regional N₂O atmospheric concentrations in the three studied catchments.</p>	<p>The data set shows that across the Namoi, Nogoia and Murrumbidgee Catchments, tropospheric SP-N₂O and δ¹⁸O-N₂O signatures are broadly consistent with mixing between terrestrial N₂O derived from agricultural activities and well-mixed tropospheric N₂O.</p> <p>In the Namoi catchment in particular the enhanced production of N₂O via denitrification pathways was accompanied by a marked increase in regional tropospheric</p>

	N ₂ O mole fraction in the main irrigated cotton growing region (up to ~336.8 ppb). This suggests that such responses to drought and the rewetting of dry soils may elicit strong production of N ₂ O that significantly contribute to regional greenhouse gas budgets.
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Part 3 – Technical Report

Projects may require different approaches to the structure of the Technical report. A detailed technical report should normally include the following items (Note - PhDs only - CRDC will accept your awarded Thesis as the Technical Report, please attach and copy and paste the abstract here):

- *Table of contents (if necessary – depends on the length and complexity of your report)*
- *Executive summary*
- *Introduction*
- *Materials and methods*
- *Results*
- *Discussion*
- *Conclusions*
- *Key word index and*
- *A full list of industry and scientific publications, presentations, extension activities and other outputs.*

Please contact your R&D manager if you would like to adopt a different approach.

We have contacted our R&D manager regarding the structure of the technical reports associated with this project. A total of 6 detailed reports, 1 PhD Thesis, 1 Honours Thesis, 10 presentations and 3 journal publications cover the outcomes of this project to date. The surface water and groundwater components are separated by river catchments (Namoi, Nogoia and Murrumbidgee River catchments) and detailed in 5 reports and 1 PhD Thesis. Atmospheric outputs are summarised in one report. Additionally, the groundwater component in the Nogoia River is also published in an open-source journal publication accessed via: <https://doi.org/10.1016/j.scitotenv.2021.152606> with a second component related to N₂O in the groundwater of the Nogoia River catchment also prepared for publication and submitted to our R&D manager for revision.

All our individual reports and publications follow the template requested above with the list of publications also detailed in this final report template elsewhere.

Part 4 – Summary for public release

This summary is designed to provide a short overview of the project for all interested parties. It will be published on Inside Cotton, CRDC's digital repository, along with the full final report (if suitable for public release). The summary may also be published on grow^{AG}, a collaborative platform that showcases Australian agrifood research, development, and extension projects that are current or have been completed since 1 July 2018. Please complete all fields, ensuring that this exceeds no more than two pages.

Project title: <i>Error! Reference source not found.</i>	
Project details:	CRDC project ID: <i>Error! Reference source not found.</i>
	CRDC goal: <i>2. Improve cotton farming sustainability and value chain competitiveness</i>
	CRDC key focus area: <i>2.1 Sustainability of cotton farming</i>
	Principal researcher: <i>Dr Dioni I. Cendón (Hydrogeochemist, Principal Research Scientist)</i>
	Organisation: <i>Error! Reference source not found.</i>
	Start date: <i>1/07/2017</i>
	End date: <i>30/06/2022</i>
Objectives	<ul style="list-style-type: none"> • Integrated assessment of N-cycle (waterways, groundwater and atmosphere) off-farm contributions in three key catchments to the Cotton industry. • Surface water quality assessment of major waterways in three cotton growing catchments: Murrumbidgee, Namoi and Nogoa Rivers. • Bi-monthly longitudinal study of nutrients, major ion and N isotopic contributions from selected sites of the three catchments studied. • Capture of a major high flow event in selected catchments to compare with dynamics observed during average or low flow conditions. • Sampling of shallow groundwater in cotton growing regions to assess potential transfers of nutrients to groundwater and potential denitrification pathways (all catchments). Specifically, in the Lower Murrumbidgee, extend the assessment to deeper aquifers. • Hydrochemical and isotopic characterisation of selected artificial end-members (i.e. fertilisers) to compare to signatures identified in the studied catchments. • Measurements of site-specific N₂O concentrations and site specific N₂O Isotopes ($\delta^{15}\text{N}^{\alpha}$, $\delta^{15}\text{N}^{\beta}$, $\delta^{18}\text{O}$) for assessing district scale nitrous oxide emissions in the studied regions.

Background	<p>The Australian cotton industry strives for responsible management of nutrients, minimising any potential transfer to the environment. However, this aspirational claim needs to be supported with detailed longitudinal studies where cotton production is a major land use. In this study a multidisciplinary team of scientist from ANSTO and UNSW looked at the nitrogen cycle from its application in the field to atmospheric and surface/groundwater loses. Three catchment portions in the Murrumbidgee, Namoi and Nogoia (Fitzroy catchment) rivers were selected for the study. Detailed isotopic monitoring of selected nitrogen species in surface and groundwater were used to assess nitrogen processes and transfer pathways to waterways and groundwater systems. The concentration of nitrogen measured throughout the landscape were compared to Australian guidelines.</p> <p>Off-farm atmospheric loses of nitrogen via nitrous oxide emissions were assessed using an LGR isotopic N₂O analyzer ($\delta^{15}\text{N}^\alpha$, $\delta^{15}\text{N}^\beta$, $\delta^{18}\text{O}$ and N₂O). All data was analysed to better understand district scale assessment of crop cycle, irrigation, weather, and nutrient application on nitrous oxide emissions.</p> <p>The three-year program captured temperature/rainfall/flood variability, apportioning nitrogen from three regions covering the two extremes of the geographical cotton distribution in Eastern Australia.</p>
Research activities	<p><i>Please provide a high level summary of the research you undertook as part of this project, to address the research need and to meet the project objectives.</i></p> <p>This off-farm project concentrated in understanding potential effects of agriculture on regional river systems, alluvial groundwater and atmosphere. Research was undertaken in three different catchments within regions with important cotton growing activity. The catchments studied were the Murrumbidgee River, Namoi River, and Nogoia River. In all three catchments, sampling was conducted in and around cotton growing areas. To achieve this objective, we used different hydrochemical and isotopic techniques. N-isotope approaches are capable of discerning processes (nitrification, denitrification, etc) and in some cases differentiate source of N-compounds (fertilisers, sewage, etc). The combination of analytical techniques deployed, and the extensive sampling offers a wide understanding of environmental processes at catchment scale that provide a valuable "baseline" in the studied regions (e.g.: water quality variations, influence of dams, timing of nutrients transport, salinity, urban inputs, etc). The research was organised in three different environmental domains: surface water (rivers), shallow groundwater and atmosphere.</p> <p>Surface water: different river sampling sites were selected for a longitudinal sampling of waters. This resulted in an approximate bimonthly sampling in each catchment for 18 months. In all catchments, the distribution of sampling sites captured river water quality <u>before</u> entering cotton growing areas and <u>downstream</u> of</p>

	<p>major cotton irrigated areas. Most river sampling coincided in all three catchments with drought conditions, providing a clear picture of river baseflow conditions under current management. Minor flooding conditions were also sampled once in all three catchments at different times, mostly coinciding with the break of the drought in 2020-2021. In all river samples we monitored an extensive number of parameters including N-compounds (NO₃, NO₂, NH₄, N₂O, DON); major ions (Na, Cl, SO₄, K, etc.); minor ions (Fe, Mn, As, Zn, etc); trace elements (Rare Earth Elements, Uranium, etc); Dissolved Organic Carbon (DOC); stable isotope ratios for many of the different dissolved compounds (NO₃, DOC, DIC, SO₄) and naturally occurring radioactive isotopes (Tritium, radiocarbon and 36-Chlorine). All data was combined to produce one of the most comprehensive datasets of water river chemistry for the selected rivers. Groundwater: shallow groundwater was sampled from monitoring wells within the three studied catchments. Selection of wells concentrated around cotton irrigation districts and was constrained by current monitoring infrastructure. Approximately 20-30 wells in each region were selected. Sampling in the Namoi and Nogoia concentrated mostly on shallow monitoring wells. In the case of the Murrumbidgee region, we also sampled at increasing depths due to the large scale of the basin and locally restricted connection of shallow groundwater system with deeper aquifers. The type of analysis performed in groundwater were as in surface water with the addition on N₂O stable isotopes to better understand processes affecting the origin and fate of N-compounds. Atmosphere: This component targeted potential N₂O emissions in the three districts. Early in our work it was realised that continuous, unattended field sampling was not possible, therefore discrete air sample bags were collected across the region coinciding with river sampling trips. All 100 samples were analysed at UNSW with a Los Gatos Research (LGR) N₂O isotope analyser, implementing protocols developed at EMPA Switzerland by PhD student Stephen Harris and presented as an associated output.</p>
<p>Outputs</p>	<p><i>Please detail the overarching outputs from this research projects: what did the project find/discover/create – be it new knowledge, technical advances etc.</i></p> <p>This project incorporates research in three different catchments with specific regional particularities in each case. When possible, we have highlighted overarching outputs. However, the wealth of data provided is of better use to CRDC at regional (catchment) scale. Surface water: All rivers studied had total dissolved nitrogen (TDN-N) near or above their respective catchment limits. However, in most cases the N-load was already present in the headwater samples, outside cotton growing regions. For example, in the Namoi River, Keepit Dam contained the highest TDN-N concentrations in 9 of 11 sampling rounds. Water releases from the respective headwater dams could be followed downstream of cotton growing areas with no major increase in TDN-N, and in some cases a decrease in TDN-N due to</p>

denitrification progressively downstream (Namoi and Nogoia Rivers). During the prevalent drought our work did not detect major point source nutrient inputs except for one sample in the Theresa Ck (Nogoia River) and regional sewage/agricultural inputs in Mirrool Ck that is mostly fed from Murrumbidgee River diversions. Water storage in the headwater dams influenced dissolved NO_3 isotopes with seasonal variations likely related to thermal stratification, such as in Keepit Dam. Extensive algal blooms related to enhanced nutrient loads took place at Burrinjuck Dam (February 10, 2021) following high flows. Most N-compound loads were carried during high flow. Detailed flooding event sampling at Theresa Ck (Nogoia Catchment) for 3 days yielded $\sim 0.58 \text{ kg/km}^2$ of dissolved inorganic N-compounds with nitrate isotopes pointing to fertiliser origin. High flow in the Namoi River during our sampling originated mostly from the Peel, Mooki and Cox's Ck catchments with nitrate isotope signatures suggesting runoff through grazing land as the dominant source of nitrate during our sampling. In the case of the Murrumbidgee River, nitrate isotope suggests a soil organic nitrogen and sewage origin. The sewage signature in addition to water quality degradation was pronounced in Mirrool Ck. This water is mostly used for irrigation or retained in different disposal sites.

Groundwater:

Shallow groundwater in all three catchments revealed that N-compounds were affected by different processes in all three catchments.

Groundwater in the **Murrumbidgee Catchment** was collected from the Murrumbidgee and Coleambally Irrigation areas from WaterNSW monitoring wells. Groundwater is used in the region for irrigation with irrigation taping mostly to the deeper Calivil and Renmark Formations with the shallower Shepparton Formation generally of poorer water quality. Isotopic data indicate that there are multiple contributors to NO_3 loads in the study area. This is presumably because of the diverse nature of irrigated farming across the region and the longer time since agricultural development started. However, the source of NO_3 can be linked to the nitrification of NH_4 derived from agricultural sources. There is a lack of connectivity between the Murrumbidgee River and the groundwater system, meaning that direct groundwater discharge of NO_3 from the Shepparton formation to the river system is unlikely, except for during floods. The greatest potential for NO_3 export appears to be where groundwater has mounded and can reach the surface using existing drainage systems. Groundwater N-compounds within the larger alluvial aquifers of the Murrumbidgee is dominated by both NO_2 and NO_3 , unlike groundwater at the Namoi Catchment (NO_3 and NH_3 dominated) or the Nogoia catchment (NO_3 dominated).

In the case of the lower **Namoi catchment**, our sampling identified different recharge mechanisms to the alluvial aquifer along the river. This includes mountain front recharge, Great Artesian Basin (GAB) input, river leakage and storage-dam leakage. TDN-N in groundwater near irrigated crops on Spring Plains Rd was higher than in other Namoi locations, and was mostly in the form of NO₃ and DON. Low NO₃ concentrations were found beneath the river floodway area (median NO₃-N = 0.3 mg/L) whilst higher concentrations were found beneath irrigated areas (median NO₃-N = 3.0 mg/L). Groundwater levels and tritium data suggest that low NO₃ groundwater from river recharge pushes outwards to mix with higher NO₃ groundwater from diffuse recharge and deep drainage below irrigation areas. Consequently, the only potential return pathway to the surface for fertiliser sourced NO₃- in groundwater below irrigation areas would be when the groundwater is pumped back to the surface. NO₃ isotope analysis suggests a fertiliser source for the NO₃ that has been re-incorporated into the soil organic nitrogen pool (through immobilisation and mineralisation) prior to being leached to the shallow aquifer. Two separate denitrification trends are apparent with samples located under irrigation areas having a slower local denitrification rate compared to the rest of samples located in the river/floodway areas. The Cardale-Mollee Rd was characterised by NH₃ and DON as main N-compounds in the groundwater. The elevated pH, low DO and elevated CH₄ concentrations related to GAB recharge identified in the area probably impact microbial population suppressing nitrification.

Nitrate in the groundwater from the Emerald Irrigation Area (**Nogoa catchment**) is derived from N fertilisers which were previously retained in the SON pool. While groundwater is not used for irrigation it reaches high concentrations of up to 24 mg/L NO₃-N. Denitrification is a key feature of the groundwater system and follows the flow path from the relatively elevated irrigation areas towards the river. Estimates of groundwater regional-scale NO₃ removal by denitrification ranges from 22 to 93%. Water quality along the Nogoa River degrades downstream from Bridge Flats Rd with increases in salinity related to local groundwater discharge. The denitrification trend along the river and nitrate isotopes support groundwater discharge is not linked to irrigation returns. The novel use of natural chloride radioactive isotopes (³⁶Cl) and the EIA setting, with only surface water irrigation, allowed to trace the mobilisation of solutes in the young EIA groundwater, as well as to trace input of modern irrigation into shallow groundwater.

Atmosphere: In addition to water-related sampling of rivers and groundwater aquifers, this project provides the first nitrous oxide (N₂O) mole fraction and isotopic composition study throughout the

	<p>Namoi, Nogoia and Murrumbidgee Catchments between 2017 and 2020. This was made possible thanks to the UNSW N₂O isotope analyser and the workflows and calibration procedures specifically developed by Stephen Harris at the Swiss Federal Laboratories for Materials Science and Technology (EMPA) as part of his PhD project. These methods have been published (Harris et al. 2020) and are currently an international reference to any researcher working on N₂O isotopic characterization by laser spectroscopy methods.</p> <p>Across the Murrumbidgee, Namoi and Nogoia catchments, N₂O signatures are broadly consistent with mixing between terrestrial N₂O (derived from agricultural activities) and well-mixed tropospheric N₂O. During one sampling campaign in the Namoi catchment, an enhanced production of N₂O via the denitrification pathway was accompanied by a marked increase in regional tropospheric N₂O mole fraction in the main irrigated cotton growing region (up to ~336.8 ppb compared to ~330 ppb in the well-mixed troposphere). This sampling campaign corresponded to a period where dry soils (caused by a prolonged period of drought) may have been re-wetted for irrigation purposes. Thus, we speculate that this increase in denitrification activity could be in direct response to prolonged drought and/or the combined rewetting/fertilisation of dry soils following prolonged drought. Due to the sporadicity of N₂O fluxes, we could not test this hypothesis with the sampling frequency employed in this Project.</p>
Impacts	<p>Please detail the impact and implications that your research will have for the Australian cotton industry, including any best practice recommendations.</p> <p>The cotton industry requires a social licence to operate. This is particularly the case in the potential extension of the industry to the north. The industry is often misrepresented in the media (https://www.abc.net.au/news/2019-02-02/are-cotton-growers-to-blame-for-menindee-fish-deaths/10763322) and numerous pressure groups oppose further development based on perceived effects on waterways (i.e.: https://cottonkillsrivers.org.au/).</p> <p>The work conducted in this project shows hard scientific data on water quality in waterways within large cotton growing areas. This work can inform current and future debate on water quality in the respective catchments and could be exported to other catchments of interest to the Cotton industry both as a baseline prior to development or as environmental control of current operations in other catchments. The work developed in this project is not restricted to one spot sampling but represents a longitudinal sampling covering bi-monthly river sampling for 18 months. We provide nutrient concentrations, general hydrogeochemistry and detailed isotope analysis from three rivers catchments (two in the Murray-Darling basin and one in the Fitzroy Basin). Results show that in most river samples, nutrients were already above specific trigger values upstream of cotton growing</p>

areas. During dry conditions, the loss of N via denitrification was identified downstream of dams as water released made its way through cotton regions, contrary to many assumptions of increases in N through cotton regions. Sampling during minor to moderate flooding conditions showed that most nutrients were transported during high flow in all three catchments. Additionally, N-isotope work suggests diverse N sources depending on river flow levels and catchments. For example, during high flow, while Keepit Dam was taking water, most nitrate in the Namoi River had values tending towards the manure range, consistent with grazing being the dominant land use overall. Other point sources (sewage) were also identified particularly in the Murrumbidgee River, where massive algal blooms took place during high flow at Burrinjuck Dam with no cotton farming upstream.

Groundwater studies were carried out within agricultural regions either dominated by cotton (Namoi, Nogoia) or wider agricultural production (Murrumbidgee). Results demonstrate that N has been historically lost to groundwater from excess fertilisers in all studied regions. Our study could isotopically determine the link to fertilisers but not a specific agricultural industry. In the case of the Nogoia and Namoi area the excessive use of fertilisers is most likely linked to cotton farming while in the case of the Murrumbidgee the large scale and diversity of crops in the region and the relatively recent development of cotton in the region points to a combination of crops. The study also revealed significant amounts of denitrification along the groundwater flow path, particularly in the Emerald region with 22 to 93% nitrate removal depending on flow paths and residence times. Groundwater discharge to rivers and shallow alluvial groundwater was identified in portions of the Nogoia and Namoi rivers but these did not contain nutrients or tracers related to agricultural practices, so could not be linked to returns from irrigation practices. No groundwater inputs were detected in the Lower Murrumbidgee River.

The atmospheric component of the study is the first of its kind in Australia on a regional scale and confirms that an "agricultural" N₂O isotopic signature (reflecting N₂O production via denitrification) can be detected in tropospheric samples taken from cotton-growing regions. The strong regional denitrification isotopic signature detected following prolonged periods of drought, and potentially during the re-wetting of drought affected soils, suggests that cropping activities during periods of drought could substantially contribute to regional N₂O budgets. This could be of relevance for capturing/accounting for greenhouse gases in cotton growing regions. However, these insights would require further verification because the frequency of our sampling could not provide adequate resolution for the variability in N₂O emission fluxes.

	<p>In general, the cotton industry and this project are proactively providing environmental scientific data of relevance to assess potential environmental impacts. This project provides key environmental data to the Cotton Industry, data that can be used to: 1) demonstrate a proactive approach to environmental management; 2) show investment in cutting-edge environmental scientific research; 3) develop a holistic approach to assessing environmental impact (surface water, groundwater and atmosphere); 4) Use as template in future areas of cotton growth to establish baseline conditions of catchments.</p>
<p>Key publications</p>	<p>Cendón, D.I., Hankin, S., Harris, S., Peterson, M., Dimovski, C., and Kelly B.F.J (2021) Quantifying the N-cycle: hydrochemistry and isotopes in the Nogoa River (QLD). ANSTO/C1745 A report to the Cotton Research and Development Corporation. August 2021, 84 pp.</p> <p>Hankin, S., Cendón, D.I., Harris, S.J., Peterson, M.A., Dimovski, C., Kelly, B.F.J. (2022). Quantifying the N-cycle: hydrochemistry and isotopes in the Namoi River. ANSTO/C1763, prepared for the Cotton Research and Development Corporation, November 2021, 95 pp.</p> <p>Cendón, D.I., Hankin, S., Harris, S., Peterson, M., Dimovski, C., and Kelly B.F.J (2022) Quantifying the N-cycle: hydrochemical and isotopic composition of the Murrumbidgee River (NSW). ANSTO/C1803 A report to the Cotton Research and Development Corporation. May 2022, 90 pp.</p> <p>Hankin, S., Cendón, D.I., Harris, S.J., Peterson, M.A., Dimovski, C., Kelly, B.F.J. (2022). Quantifying the N-cycle: hydrochemistry and isotopes of shallow groundwater in the Lower Namoi Alluvium. ANSTO/C1808, prepared for the Cotton Research and Development Corporation, June 2022, 64 pp.</p> <p>Harris, S.J. Cendón, D.I., Hankin, S.I., Peterson, M.A., Shuang Xiao, Kelly, B.F.J. (2022) Isotopic evidence for nitrate sources and controls on denitrification in groundwater beneath an irrigated agricultural district. Science of the Total Environment, 817, 152606. https://doi.org/10.1016/j.scitotenv.2021.152606</p> <p>Harris, S.J., Cendón, D.I., Barthel, M., Hankin, S., Peterson, M.A., Six, J., Kelly, B.F.J. (2023). Attributing N₂O production pathways and reduction to N₂ in groundwater using an isotope mapping approach. To be submitted to Biogeosciences.</p> <p>(not funded by CRDC but directly linked to our CRDC project) Harris, S.J., Lissberg, J., Xia, L., Wei, J., Zeyer, K., Yu, L., Barthel, M., Wolf, B., Kelly, B.F.J., Cendón, D.I., Blunier, T., Six, J. and Mohn, J. (2020) N₂O isotopocule measurements using laser spectroscopy:</p>

	analyzer characterization and intercomparison. Atmos. Meas. Tech. 13, 2797-2831. https://doi.org/10.5194/amt-13-2797-2020
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