Land-Use Futures Project - LUTO 2.0 Model Description

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Background

LUTO 2.0 is version two of the Land-Use Trade-Offs model of Australian land-use. It is freely available online on GitHub <https://github.com/land-use-trade-offs/luto-2.0> (including an example input dataset required to run the model) published as open source under GNU GPLv3 license in 2022. Development of the LUTO 2.0 modelling framework is led by Professor Brett Bryan, Deakin University as part of the Land-Use Futures program—a collaboration between ClimateWorks Centre, Deakin University, and CSIRO. The model should be cited as:

* Fjalar de Haan, Carla Archibald, Michalis Hadjikakou, Shakil Khan, Raymundo Marcos-Martinez, Javier Navarro, Asef Nazari, Dhananjay Thiruvady, and Brett A Bryan. (2022). LUTO 2.0 (Land-Use Trade-Offs Model Version 2.0). License: GPL-3.0+.

The model projects the spatial distribution of future land-use for Australia which meets exogenously-specified demand for Australian agricultural production at minimum economic cost (or maximum economic profitability) under various constraints, including environmental limits such as water use and greenhouse gas emissions. The model is contained in a Python package (the *framework*) and can be run interactively for a single scenario or in batch mode (e.g., for many scenario runs on a compute cluster).

LUTO 2.0 continues the approach to land-use change modelling of its predecessor, the original LUTO version 1.0, which was developed by CSIRO from 2010-2015 and published under the GNU GPLv3 in 2021. The code for the original LUTO model and results of a major scenario analysis have been extensively published.[[1]](#footnote-2)

LUTO 2.0 is similar to the original LUTO in terms of its basic approach to land-use change modelling. In particular, aspects like discretising the land-use map at a 1x1 km grid cell resolution and representing it as a 1D array with land-uses as integers. LUTO 2.0 is, however, an entirely new model—written completely from scratch—with no original LUTO 1.0 code remaining in the LUTO 2.0 code base and the entirety of the input data has been updated. Being a demand-driven model, the economic logic governing land-use change in LUTO 2.0 is also different from the profit maximisation, policy analysis logic of the original LUTO 1.0.

LUTO is currently at version 2.0.3 and is under continuous improvement and extension in both code and data, with new functionality coming online regularly. New updates can be found in the GitHub repository linked above.

What the LUTO model does

The original LUTO (i.e., version 1.0) is based on the assumption that farmers try to maximise their profits (i.e., maximise producer plus consumer welfare, or *net social welfare*) in response to changing prices and financial incentives for different land-uses (e.g., carbon price, biodiversity payment scheme, bioenergy industry). As supply of agricultural commodities changes due to competition for land from the uptake of new land-uses, so does the price of commodities via a partial equilibrium approach based on downward sloping demand curves. LUTO 1.0 was designed as a policy analysis tool which projected the potential outcomes of a range of economic incentive and regulatory (i.e., land-use planning) policy on land-use. The impacts of land-use futures were then assessed across a range of economic and environmental indicators.

The leading LUTO 2.0 assumption is that the overall agricultural system meets an exogenously specified demand at minimum cost of production (including costs of switching between agricultural commodities/land-uses) or maximum net economic returns (the choice of cost minimisation or profit maximisation is specified in the model settings). Demand is calculated in quantity terms by a new econometric demand model which estimates the total production expected from Australian agriculture given global settings (e.g., GDP, wealth per capita, population, trade assumptions, diet, and food demand) and domestic settings (e.g., population, diet, agricultural export orientation). Environmental limits (i.e., planetary boundaries) can also be set in LUTO 2.0, enabling the model to spatially allocate agricultural and new land uses which also meet environmental limits (e.g., maximum GHG emissions, no new species extinctions, limits to water use, etc.). LUTO 2.0 then calculates the impact of land-use across a range of key indicators of natural capital and sustainability.

A major limitation with the original LUTO was that it only allowed land-use switching from current (2005) land-use (i.e., one of 23 agricultural commodities) to an alternative land-use (i.e., carbon plantings, wheat biofuels) and land-use could not switch between agricultural commodities (e.g., beef cattle could not switch to wheat cropping). Hence, LUTO 1.0 did not allow for effective analysis of the major emerging demand-side interventions for greenhouse gas mitigation (e.g., diet change). LUTO 2.0 now features full commodity switching between all land-use types (i.e., agricultural commodities can change in response to changes in food demand).

Both LUTO versions are linear programming optimisation models but different commercial solvers are used (CPLEX in original LUTO, GUROBI in LUTO 2.0). The spatial domains are different in extent, with LUTO 2.0's being around 9 times larger and covering the entire Australian land mass (LUTO 1.0 covered only the intensive agricultural zone). The data and compute requirements to run LUTO 2.0 are consequentially different and much heavier. LUTO 1.0 covered the time horizon from 2013 to 2050 whereas LUTO covers the years 2010 to 2100 to be consistent with long term climate projections. All input datasets have been updated, improved, and extended in both spatial and temporal coverage. There is no backwards compatibility between LUTO versions whatsoever.

LUTO 2.0 technical enhancements

LUTO version 2.0 has many enhancements over the original LUTO version 1.0. Model enhancements were discussed and decided upon following extensive consultation with stakeholders and the Land-Use Futures project Technical Reference Panel. Enhancements are detailed below along with a note explaining the status of the enhancement ranging from drawing board idea (red) to data modelled but not yet implemented/integrated within LUTO 2.0 (orange), to fully modelled and implemented/integrated within LUTO 2.0 (green).

* Python 3. LUTO 1.0 was built in Python 2.7 which is now deprecated. We ported the full LUTO 1.0 model to Python 3.0 and developed LUTO 2.0 entirely in Python 3.0.

[STATUS: fully implemented]

* Modelling time horizon. LUTO 1.0 time horizon spans the years 2013 to 2050. The LUTO 2.0 time horizon has been extended to range from 2010 to 2100 to align with other global models and allow long term projections (e.g., to assess long term climate change or population impacts). All input data has been updated to the longer time series.

[STATUS: fully implemented]

* Snapshot and timeseries runs. LUTO 1.0 runs annually from 2013 to 2050. LUTO 2.0 can run either annually from any start year to any end year, or it can run for a single snapshot year from 2010 to 2100 (e.g., 2050, 2100), including ‘current’ or ‘historical’ analyses for 2010.

[STATUS: snapshot runs fully implemented, annual time series partially implemented] [PRIORITY: High]

* Spatial extent expanded. LUTO 1.0 considers the intensive agricultural zone, an area of around 800,000 km2. LUTO 2.0 covers the entire continental Australian land mass, an area of around 7,000,000 km2 and 1 x 1 km grid cell resolution. The new study area incorporates the extensive beef grazing systems of northern Australia (an important export market and source of the potent greenhouse gas methane) as well as unallocated agricultural land and natural areas (including private land, public land, areas under formal protection for nature conservation, native title, indigenous management, etc.). This region has important implications for livestock and meat supply, GHG emissions, land clearance, and biodiversity.

[STATUS: fully implemented].

* Spatial coarse-graining. LUTO 1.0 can be run at full resolution (1km2 grid cells) or at a coarser spatial resolution which approximates the high-resolution run but solves in much shorter compute time to support testing/multiple runs. LUTO 2.0 also has this facility.

[STATUS: fully implemented]

* Updated global scenarios. LUTO 1.0 used bespoke ‘Global Outlooks’ as scenarios developed as part of the Australian National Outlook 2015. LUTO 2.0 has been updated to use the latest combination of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) developed by the international integrated assessment community. The 4 SSP/RCP Tier 1 combinations from ScenarioMIP are used including SSP1\_RCP2.6, SSP2\_RCP4.5, SSP3\_RCP7.0 and SSP5\_RCP8.5.

[STATUS: fully implemented].

* Complete input data refresh. All original LUTO 1.0 input data layers have been updated, enhanced, expanded to the new territory, and extended to the new timeline. In addition, many new spatio-temporal data sets have been created for both agricultural and new land-uses and to provide new sustainability indicators. The input data for the LUTO model is substantial and highly dimensional (i.e., combinations of ~7M grid cells, 91 years, 4 scenarios, 8 GCMs, multiple land-uses, multiple indicators), hence running into some tens of gigabytes. Some of the major data upgrades include:
  + Land-use mapping. Baseline land use map has been updated to the year 2010 based on the 2010 Australian National Land-use Map, extended by CSIRO to include pixel-level livestock mapping (i.e., beef, dairy, sheep) based on ABS AgStats and the AussieGrass pasture growth model.

[STATUS: fully implemented].

* + Agricultural yield and economic data. Agricultural yield, costs of production, water requirements, and price data underpinning LUTO 2.0 has been completely recalculated to provide long term average baseline values for 2010 based on data from 2005 – 2015 inclusive. The data is from a range of sources including the ABS agricultural census, gross margin handbooks, AussieGrass pasture growth model, and other ABS data. The data includes livestock stocking rate and yield estimates, along with economic and production data for ‘off-land’ commodities of chicken, pork, and eggs. To enable agricultural commodity switching, the agricultural data is now ‘space filling’, whereby every grid cell has data for every potential commodity which it may support.

[STATUS: fully implemented]

* + Off-land commodities. Pork, poultry, aquaculture, and alternative protein sources (i.e., future foods such as lab meat, mycoprotein) including their demand for crop-based feed and feed efficiency, feed composition (% grass versus grain) scenarios for different livestock sectors have been modelled. In conjunction with the shift to demand-based land-use allocation, these solutions enable us to assess transformative shifts in diet to meet future global and domestic food demand scenarios.

[STATUS: fully modelled but not yet implemented in LUTO 2.0] [PRIORITY: High]

* + Agricultural environmental impacts. Greenhouse gas emissions from agriculture have been specified at the level of individual gases (i.e., CH4, N2O, CO2) from specific components of the farming system from lifecycle assessment and gross margin handbooks. Nitrogen and phosphorus application rates have been calculated based on gross margin handbooks. Nitrogen and phosphorus surplus/loss have been calculated based on crop yield estimates. Impacts of agrochemicals such as pesticides and herbicides used in the production of agricultural commodities on human health and the health of aquatic ecosystems have been calculated based on the UN USETOX model.

[STATUS: agricultural GHG emissions have been partially implemented in aggregate form as CO2e. N, P etc. have been fully modelled but not yet implemented in LUTO 2.0] [PRIORITY: High]

* + Climate change. Climate change projections for the 4 SSP/RCP combinations have been updated from CMIP3 to the latest CMIP6 estimates, and 8 global climate models are used in LUTO 2.0 (BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, IPSL-CM6A-LR, MIROC-ES2L, MIROC6, MRI-ESM2-0), up from 3 in LUTO 1.0. Parameters include minimum temperature, maximum temperature, rainfall, potential evapotranspiration calculated using the Priestley Taylor method, and 19 bioclimatic parameters. Time periods include historical plus 2021-2040, 2041-2060, 2061-2080, 2081-2100 interpolated to produce annual estimates.

[STATUS: fully implemented]

* + Agricultural productivity. The spatially explicit impact of climate change on the productivity of all 28 agricultural commodities and pastures has been quantified under each SSP/RCP combination using the Global Agroecological Zones (GAEZ) model version 4.0. LUTO 1.0 used APSIM modelled estimates for wheat to represent the impact of climate change across all crops and livestock.

[STATUS: fully implemented]

* + Water yield. Catchment water yield and the spatial distribution of water yield (i.e., the contribution to water yield of each cell) has been calculated under each SSP/RCP combination using the Budyko framework incorporated in the InVEST model and based on a digital elevation model and soil data from the Soil and Landscape Grid of Australia. The effect of changes in rainfall and potential evapotranspiration and the impact of reforestation and land clearance on water yield has also been quantified under all climate scenarios.

[STATUS: fully modelled but not yet implemented in LUTO 2.0] [PRIORITY: High]

* + Biodiversity. The spatial distribution of habitat suitability for 10,608 species (1,356 terrestrial vertebrates and 9,252 vascular plants) has been quantified by integrating Atlas of Living Australia records with species distribution modelling under each SSP/RCP combination. Spatially explicit biodiversity priorities for restoration were identified using the Zonation core method combined with principles from landscape ecology. LUTO 1.0 included only a single integrated layer of biodiversity priority score values calculated using Generalised Dissimilarity Analysis.

[STATUS: fully modelled but not yet implemented in LUTO 2.0] [PRIORITY: High]

* + Soil erosion and sedimentation. Combining runoff calculated using the InVEST model, soil erosion, deposition, and waterway sedimentation was calculated based on the revised universal soil loss equation (RUSLE) under all climate scenarios. Mitigation of soil erosion and sedimentation by different land-use/cover types was also captured.

[STATUS: fully modelled but not yet implemented in LUTO 2.0] [PRIORITY: High]

* + Carbon sequestration. Sequestration of carbon in above ground biomass, below ground biomass, and soils was calculated for a range of ERF-compliant land-uses including mixed species environmental plantings, hardwood plantations, mallee plantations, and human induced regeneration. A range of planting densities were also calculated, along with different planting arrangements (belt, block, and riparian plantings). Spatially explicit modelling over a 100-year timeframe was undertaken using the Australian Government’s FullCAM model.

[STATUS: fully modelled but not yet implemented in LUTO 2.0] [PRIORITY: High]

* + Bioenergy with Carbon Capture and Storage (BECCS). Spatially-explicit model of mallee-based BECCS electricity production identifies the location of mallee plantations based on FullCAM-estimated biomass production and proximity to existing power plants, the electricity grid, and suitable geological structures for carbon capture and storage. This enables us to understand the potential GHG mitigation capacity of BECCS in Australia for carbon sequestration, the electricity produced, the costs, and the best locations for this solution to be applied.

[STATUS: fully modelled but not yet implemented in LUTO 2.0] [PRIORITY: Low]

* Demand model. By combining econometric modelling of timeseries historical data, the demand model predicts the total demand (in quantities) for 30 key Australian agricultural commodities into the future. It considers different drivers of that demand each of which is handled by a different module, namely domestic demand (demand from the Australian population), trade (demand associated with exports/imports), and livestock feed (demand for crops and pasture used as feed for livestock). The model is flexible in that it allows the incorporation of global and domestic scenario assumptions around population, income, diets, food loss and waste, and crop and livestock productivity. Projected demand for Australian agricultural production is then exogenously input into LUTO 2.0.

[STATUS: fully modelled but needs to be tightly integrated and automated with LUTO 2.0 such that demand scenarios are run as a routine part of a LUTO run] [PRIORITY: High]

* Constrained dynamic land-use change allocation engine which meets food demand within environmental limits. In LUTO 1.0, grid cells are mapped as agricultural commodities following the national land use map and remain as that commodity type unless outcompeted by a new land-use such as environmental plantings. In LUTO 2.0, agricultural commodities can switch between different types (within land capability) and can switch to new land-uses or land management types such that exogenously defined agricultural demand (i.e., from the demand model or any other model or scenario specification) and/or environmental limits are met. To support this, full agro-economic and environmental data for each agricultural land-use has been quantified for each grid cell for each year under each scenario. In addition, a matrix of transition costs quantifies the cost of transition from one type (e.g., sheep grazing) to another (e.g., wheat cropping). Similarly, the same space-filling economic and environmental information needs to be produced for all new land use and Land Management solutions to be implemented in LUTO 2.0. We have quantified [environmental limits for Australia](https://www.climateworkscentre.org/wp-content/uploads/2022/04/LUF_PB-summary-report_FINAL.pdf) and these can be set as hard constraints or aspirational targets within the land-use allocation engine such that land-use is allocated to grid cells such that agricultural demand is met within environmental limits.

[STATUS: partially implemented. The model allocates agricultural land-uses such that food demand is met within limits for water use and greenhouse gas emissions. New land-uses and land management types are yet to be implemented] [PRIORITY: High]

* Solve using Gurobi. LUTO 1.0 used the commercial solver CPLEX to solve the constrained land-use allocation linear program. This relied upon an in-house CSIRO-developed library called pyCPLEX to interface between LUTO’s Python Numpy data structures and the CPLEX solver. pyCPLEX was developed around 2013 and is no longer supported and had to be extensively debugged to get it to work with the Python 3 version of LUTO 1.0. We developed LUTO 2.0 using the Gurobi commercial solver. Gurobi, now in version 10, offers a fully supported GurobiPy library with an API which provides advanced tools for interfacing between Gurobi and the Python Numpy/Pandas data structures used in LUTO 2.0.

[STATUS: fully implemented]

* Broad scale land-cover change. LUTO 1.0 considered Australia’s intensive agricultural land-use zone only and this area remained unchanged into the future. In LUTO 2.0 we have built an [exogenous model of broad scale land cover dynamics for Australia](https://doi.org/10.1016/j.rse.2020.112148) at high resolution (30m resolution) which is capable of projecting the spatial extent of urban expansion under future scenarios which align with the SSPs. This spatial model of urban expansion can be used to constrain the area of land available for agricultural production in LUTO 2.0. Dynamics around the expansion of agriculture into natural land and the converse process of agricultural land abandonment are already built into LUTO 2.0.

[STATUS: urban model completed but not implemented in LUTO 2.0] [PRIORITY low]

* New sustainability indicators. LUTO 2.0 includes many of the sustainability indicators used in version 1.0 (refreshed and updated), as well as several new indicators developed for use in assessing the impact of land-use and land-use change over time. Indicators were designed to provide estimates of base accounts of natural capital and align with the UN System of Environmental and Economic Accounting. These indicators include estimates of the following over space and time:
  + Agricultural production [STATUS: fully implemented]
  + Commodity prices [STATUS: fully implemented. Option added to maximise profit.]
  + Economic returns to agriculture [STATUS: implemented in the model but reporting not complete] [PRIORITY: High]
  + Net GHG emissions (carbon emissions – sequestration) [STATUS: implemented for agriculture, avoided deforestation and sequestration from new land-uses and land management types needs to be added] [PRIORITY: High]
  + Water use [STATUS: implemented for agriculture, water use by new land-uses needs to be added] [PRIORITY: High]
  + Catchment-level water stress [STATUS: fully modelled but not yet implemented] [PRIORITY low]
  + Species habitat and biodiversity [STATUS: fully modelled but not yet implemented] [PRIORITY: High]
  + N and P use and loss [STATUS: fully modelled but not yet implemented] [PRIORITY: High]
  + Soil erosion and sedimentation [STATUS: fully modelled but not yet implemented] [PRIORITY: High]
  + Agri-chemical impacts on human and ecosystem health [STATUS: fully modelled but not yet implemented] [PRIORITY: High]
  + Renewable electricity [STATUS: fully modelled but not yet implemented] [PRIORITY low]
* New land-use and food system sustainability solutions. Dozens of new solutions both on the supply side (i.e., on-ground actions involving changes in land use/management) and the demand side (i.e., which alter the quantum of food produced by Australian agriculture) have been evaluated and prioritised for inclusion in LUTO 2.0. On the supply-side, these fall under the general headings of protecting and restoring nature, increased productivity/sustainable intensification, conservation/regenerative agriculture, off-land food production, climate change adaptation, breakthrough technologies, boosting fibre production, carbon sequestration. On the demand-side, these include a shift towards healthy and sustainable diets, diversifying sources of animal protein, novel sources of protein, waste reduction and circular economy measures, energy system and value chain decarbonisation. We have undertaken an extensive literature review to parameterise the economic cost and environmental impacts of many supply-side solutions identified as high priority but these have not yet been implemented in LUTO 2.0. For the demand-side solutions, many of these have been parameterised and have already been incorporated into the demand model and are fully implemented in LUTO 2.0.

Supply-side solutions [STATUS: parameterised but not yet implemented] [PRIORITY: High]  
Demand-side solutions [STATUS: parameterised as part of the demand model but needs to be more tightly integrated and automated as part of LUTO 2.0] [PRIORITY: High]

* Mosaic land-uses. Mixed agricultural practices and agricultural mosaics such as alley farming or reforesting creeklines need to be added. This can address the demand for considering multiple land-uses within each cell. We have made some progress towards this including quantifying the carbon sequestration of riparian vegetation and quantifying the areas of riparian buffers along creek lines as specified by the Bureau of Meteorology Geofabric stream data.

[STATUS: parameterised but not yet implemented] [PRIORITY: High]

Summary of the status of the LUTO 2.0 model at 2 Aug 2023. LUTO 2.0 is a fully functional constrained dynamic land-use allocation model which can take exogenously specified demand for Australian agricultural production and allocate land-use and land management (i.e., dryland/irrigated) to grid cells which meet demand at minimum cost/maximum profit. Irrigation is also constrained to allow water trading but include constraints such that total water use remains within aggregate limits at the catchment/basin level. Demand is calculated via the demand model and can be specified according to a range of scenarios of global and domestic population, wealth, consumption, waste, and diet assumptions. Greenhouse gas emissions targets can be specified as constraints for agriculture.

1. Bryan, Brett; Nolan, Martin; Stock, Florian; Graham, Paul; Dunstall, Simon; Ernst, Andreas; Connor, Jeff (2021): Land Use Trade-Offs (LUTO) Model. v1. CSIRO. Software Collection. <https://doi.org/10.25919/y8ee-sk45>.

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