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3 **Stock to crop? Quantifying agricultural expansion in northern Australia**
4 **and examining its drivers**

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Abstract

In recent decades, local, state, and federal governments have actively promoted irrigation and rainfed cropping expansion as a pathway to regional economic development for inland northern Australia (INA). This has created tension and competing narratives about development in the region. This study seeks to ground discussion in observed patterns of change by synthesising the cropping, horticulture and plantation forestry land use changes across INA between 1999 and 2023. Agricultural land use was mapped using the latest jurisdictional datasets and Sentinel-2A imagery in 2023 and Landsat-7 imagery in 1999. Land use was augmented by adding information on commodity type, land tenure, remoteness, irrigated water source and irrigation system. Irrigated agriculture grew from 32,904 to 60,303 ha, which is about 3% of the area of INA estimated as physically possible to irrigate based on coincidence of soil suitable for agriculture and water. Rainfed cropping and plantation forestry expanded from 28,811 to 134,362 ha. Drivers for this change in land use across the north are examined. Based on the results from the recent past we discuss what the future might hold. Future expansion is expected in regions with enabling infrastructure, cost-effective water and soils suitable for cropping.

Keywords

Irrigation; Rainfed cropping, horticulture and plantation forestry; Land use mapping; Land clearing; Water management; Rangelands

1. Introduction

The collection of land use statistics and the development of mapping products to monitor agricultural expansion or contraction is a fundamental data set used for policy and other decisions concerning how land is used and managed (Lesslie et al., 2006). However, inland northern Australia (INA), broadly that part of Australia north of the Tropic of Capricorn and west of the Great Dividing Range (defined in further detail in Section 1.1), has received relatively little attention despite its vast extent, covering over 3 million km² or 300 million hectares (ha) (40% of Australia and 2% of the Earth's land surface). This sparsely populated landscape is primarily used for extensive grazing, Indigenous use and conservation (Grice and Watson 2013; Watson et al, 2021). Growing interest in agricultural intensification of INA necessitates an examination of changes in area of irrigated and rainfed agriculture. Understanding these changes offers globally relevant insights into the drivers and constraints of irrigation expansion in a 'greenfield' region. While INA remains more ecologically intact than comparable environments worldwide (Beyer et al., 2020; Williams et al., 2022), significant concerns persist regarding land clearing and large-scale water resource development, with many advocating for conservation and sustainable management of the region in its current state (Woinarski et al., 2007; Blanch, 2008). Agricultural intensification is perceived as a potential environmental threat (Williams et al., 2022), compounding existing pressures from the grazing industry (Runting et al., 2024). Additionally, Indigenous Australians, who comprise nearly 18% (230,000) of northern Australia's population (Office of Northern Australia, 2024), hold diverse perspectives on agricultural development (Barber and Woodward 2018, Taylor, Thurmer and Karácsonyi, 2022; Jackson et al., 2023). While many Indigenous communities are not inherently opposed to development (Langford, Lawrence and Smith, 2021), they consistently relate concerns over the

potential type and scale of agricultural development and who would benefit (Stephens *et al.*, 2015; Barber and Woodward, 2018).

The challenges associated with agricultural intensification in northern Australia (NA) are well documented and include factors such as remoteness (Davidson, 1965), lack of patient capital, supply chain limitations (Babacan and McHugh, 2020), the risks of rapid scaling (Ash and Watson, 2018) and weaknesses in value chain propositions (Ash *et al.*, 2017). Despite ongoing debates regarding agricultural intensification, it remains difficult to quantify net changes in agricultural land use in NA from existing data sources. A notable exception is the horticultural industry, which recently conducted a sector-wide analysis of constraints to development in the north (Sangha *et al.*, 2022). Consequently, discussions often occur at ‘cross-purposes’ with some stakeholders assuming that vast tracts of land may be developed (e.g. Moran-Ordóñez *et al.*, 2017) while others argue that such developments will remain negligible. A more informed debate requires high-quality, standardised and widely accessible foundational data.

Globally, the Food and Agriculture Organization (FAO, 2023) estimated that in 2021, 352 million ha of land were equipped for irrigation, 22% of the total cropped area, with Oceania having the largest area of cropped land per capita (0.8 ha/cap). However, existing global land use datasets vary considerably in their estimates. Across six mapping products, estimates of irrigated areas for Australia range from 2,465,000 to 11,865,200 ha (Meier, Zabel and Mauser, 2018). Also, these global data sets lack the resolution necessary for sub-continental, catchment or regional analyses. Across northern Australia, the most comprehensive published land use datasets are composites of mapping products developed independently by Western Australia (WA), Northern Territory (NT) and Queensland (Qld) governments using national standards (ABARES, 2024) at points in time. However, variations in data collection methods, reporting years, classification schemes, and validation approaches hinder the ability to derive

accurate, region-wide assessments of land use trends. Furthermore, available datasets rarely integrate critical biophysical parameters such as mean annual rainfall, [Click or tap here to enter text.](#) soil type, land tenure or water source, limiting their utility for understanding agricultural constraints and opportunities. As a result, it is not possible to confidently undertake an analysis of change across the whole of INA without first undertaking a standardised remapping effort.

This study standardises land use mapping across the three northern jurisdictions and refines classifications for cropping, horticulture, and plantation forestry at two time points (1999 and 2023). Using satellite imagery, publicly available datasets, media reports and expert knowledge, this analysis provides the first comprehensive synthesis of trends in irrigated and rainfed cropping over a 24-year period for INA, with the period chosen because of the availability of consistent data across the jurisdictions. The resulting dataset offers insights into the trajectory of agricultural development in INA, informing future policy, investment, and sustainability strategies.

1.1 Study area

Most of NA is sparsely populated and development of agricultural land is mainly restricted to land currently used for extensive cattle grazing for beef production, except along the eastern coast of Qld. As discussed by (Petheram and Bristow, 2008) this coastal region is geomorphologically (e.g. rivers drain steep coastal escarpments) and climatically (e.g. receives dry-season rainfall) distinct from INA. Furthermore, there are already large established areas of irrigated and rainfed cropping, horticulture and plantation forestry and there are several large cities such as Rockhampton (83,000), Townsville (200,000) and Cairns (175,000). INA is not a formal regionalisation and can be delineated several different ways, largely based around the idea of being ‘north of the Tropic of Capricorn’ (ToC). Here we take

the definition as used by the Australian Government (Office of Northern Australia, 2024) with some adjustment, as outlined below.

The study area is defined as follows, that part of northern Australia west of the Great Dividing Range and north of the ToC (Latitude -23.44) but including all the NT (including the Tiwi Islands), and the Gascoyne catchment in WA. Except for the Tiwi Islands, no other offshore islands are included in INA because they did not have significant areas of cropping, horticulture or plantation forestry. This definition of INA encompasses an area of 308,414,465 ha or 40% of Australia's landmass (768,828,700 ha)(Geosciences Australia, 2024)) (Figure 1). For geographic context, Australia's 'food bowl' the Murray Darling Basin (MDB) is shown.

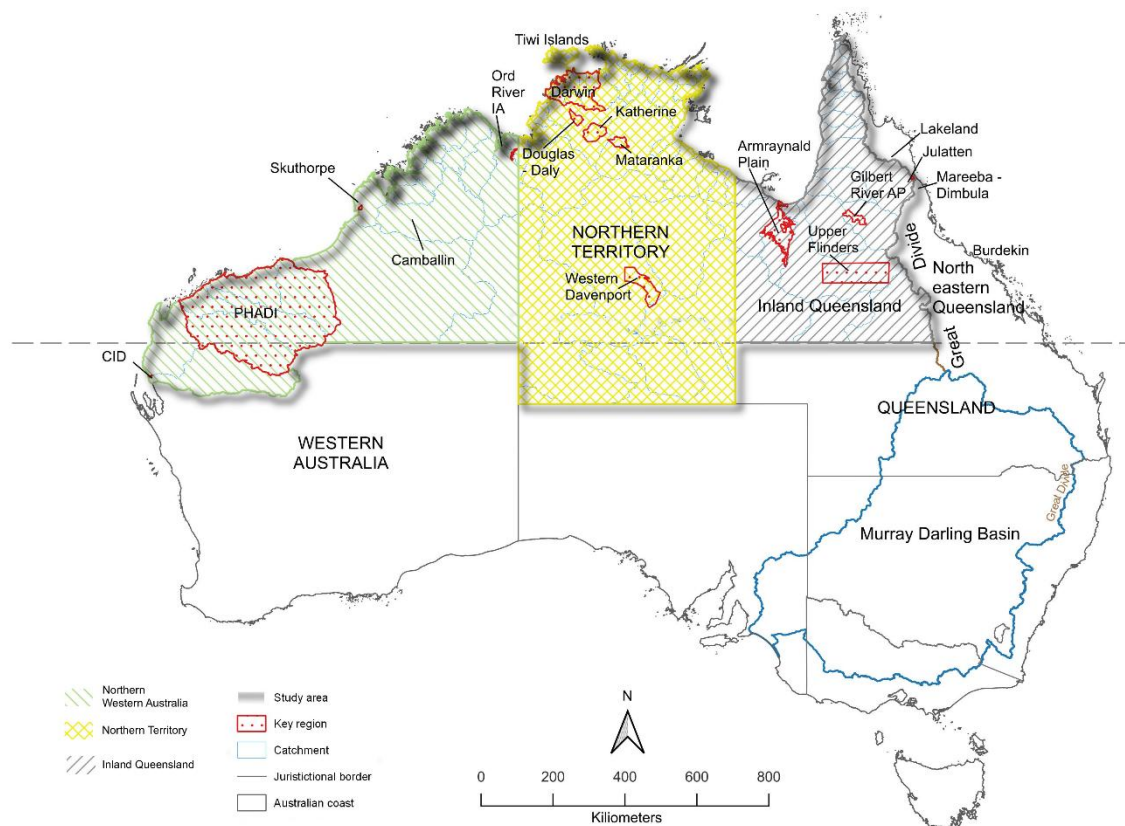


Figure 1 – The area defined as inland northern Australia, including Australian Water Resource Council (AWRC) catchment and jurisdictional boundaries. Key regions are delineated. A number of places referred to in the text are also shown.

There are 71 whole or part river catchments (ARMCANZ, 1997) and one island archipelago (Tiwi Islands) in the study area. For reporting purposes, six of the river catchments are further divided into two parts due to a jurisdictional boundary coinciding within the catchment. In total this gives 77 reporting units.

Within the study area 13 key regions have been identified, which are aggregations of cropping and horticulture that have already developed or there are current plans for such development. These key regions do not necessarily coincide with the reporting units, and most have no formal boundary. However, they have been delineated here based on water resource plans and/or government policy and expert judgement as places that have had or are undergoing notable agricultural change. Figure 1 shows their locations and Table 1 describes the key region.

Table 1 - Description of key regions within inland northern Australia from west to east. Note that the extent (ha) reflects the size of the general area of each key region. In most cases, agricultural intensification would only occupy a small proportion of the key area – except for those already well developed, such as the Carnarvon Irrigation District and Julatten.

Name	Established (Year)	Extent (ha)	Nearest population centre	Jurisdiction	Details	Reference
Carnarvon Irrigation District	1962	4000	Carnarvon	WA	Regulated groundwater irrigation area on alluvial lands along the Gascoyne River	
Pilbara Hinterland Agricultural Development Initiative (PHADI)	2017	24,026,623	Port Hedland	WA	Established to assess the potential for irrigated agriculture in the Pilbara. Area comprised of the Port Hedland Coast and DeGray, Fortescue and Ashburton catchments	(DPIRD, 2024b)
Skuthorpe	1991	370	Broome	WA	Proclaimed groundwater irrigation area	(DWER, 2024)
Ord River Irrigation	1963	21,400	Kununurra	WA	Stage 1- Kununurra & Packsaddle Plains (140 km ²) & Stage 2 – Weaber Plain (74 km ²)	(DPIRD, 2024a)

Name	Established (Year)	Extent (ha)	Nearest population centre	Jurisdiction	Details	Reference
Area (ORIA)						
Central plains of Western Davenport	2021	1,042,200	Tennant Creek	NT	A developing groundwater irrigation area	(NTG, 2021)
Mataranka	1942	551,358	Mataranka	NT	Developing groundwater irrigation area which began with an Australian Army farm that was growing fresh produce for Army troops stationed in the NT.	(Cronk, 2011)
Katherine	1942	595,114	Katherine	NT	Established cropping and horticultural area which began with an Australian Army farm that was growing fresh produce for Army troops stationed in the NT.	(Cronk, 2011).
Douglas – Daly	1970s	206,176	Pine Creek	NT	The lower reaches of the Daly River and its tributary, the Douglas, in the northern part of the NT have become an extensive cropping area. Development has been guided by an agricultural research station that was established in 1965.	(Shotton, 2011)
Darwin Rural Area	1940s	696,400	Darwin	NT	An extensive horticultural industry has developed around the capital city of the NT using groundwater for irrigation. The area is defined by the Adelaide, Finniss, Mary and Wildman catchments.	(Petheram <i>et al.</i> , 2018)
Upper Flinders	1938	5,485,850	Hughenden	Qld	Located between Julia Creek and Hughenden and subject of several	(Petheram <i>et al.</i> , 2020)

Name	Established (Year)	Extent (ha)	Nearest population centre	Jurisdiction	Details	Reference
					irrigation scheme proposals since the Bradfield Scheme was first proposed. Currently there is dispersed development throughout the area.	
Armraynald Plain	2020	1,294,400	Burketown	Qld	Located between the lower reaches of the Nicholson and Leichhardt Rivers in the Gulf of Carpentaria region. Area first named as the Plains of Promise by John Stokes in 1841 and has been the focus of several irrigation studies. Currently crops are being trialled	(Watson <i>et al.</i> , 2024)
Gilbert River Agricultural Project	1998	252,100	Georgetown	Qld	Located on alluvial lands along the Gibert river in the Gulf of Carpentaria region of Qld, this area has been the focus of several development proposals.	(Etheridge Shire Council, 2021)
Julatten	1920s	12,100	Julatten	Qld	Located in the eastern part of the Mitchell catchment, this is an established sugarcane producing area. Cane is processed at Mareeba mill located within Eastern Qld.	

2. Materials and methods

Agricultural land use (cropping, horticulture and plantation forestry) spatial data were created across INA for the calendar years 1999 and 2023. The most recent (at the time) land use mapping from the three northern jurisdictions was used as a starting point. For WA, this was land use mapping completed in 2018 but including comparison data from 2008 (ABARES and DPIRD, 2018). NT data were completed in 2022 (Anon, 2022) but data were also available from 2003 (DENR, 2003). Qld data came from the Australian Collaborative Land Use Mapping Program (ACLUMP) released in December 2020 (ABARES, 2021) which contained data from a range of dates in inland Qld (e.g. 2013 for much of Cape York) as well as data from 1999 (Anon, 2019). These datasets were used as the baseline, with Landsat and Sentinel imagery subsequently examined to check, update and refine the mapping and incorporate additional ancillary information. Landsat 7 (Fuqin *et al.*, 2019) imagery were acquired for the year 1999 (~12 passes along each path were available) and Sentinel 2A (Geoscience Australia, 2022) imagery acquired for the year 2023 (~36 passes along each path were available). The 1999 data is the oldest available daily Landsat 7 data and has a 30m resolution which is the best available data for that time. Land use was manually recorded in a geographic information system (GIS) as polygons in the ESRI shapefile format. Each polygon was attributed with the Australian Land Use and Management Classification (ALUMC) numeric code (ABARES, 2016) for agricultural land uses (Class 3 and 4). ALUMC organise land uses by how much humans change the environment from its natural state. Class 3 refers to production from dryland (i.e. rainfed) agriculture and plantations, and Class 4 refers to production from irrigated agriculture and plantations.

Rainfed pastures with a mix of native and modified species (Class 3.2) were not included. Modified pastures are typically a mixed sward of native and introduced (often naturalised)

species where cultivation is not used, and seeding is via wide-area broadcast (sometimes from aircraft). That is, these modified pastures are not considered typical rainfed or irrigated cropping.

The land use was deemed to exist if it was visible on the satellite imagery at any time during 1999 or 2023, and multiple scenes were usually manually examined at each location to populate auxiliary information. Because the analyses only require the existence of a single cloud free scene, the method is not sensitive to the presence of cloud. Presence or absence of irrigated or rainfed land uses in other years except the years 1999 or 2023 were not considered. For example, if an irrigation development started in the year 2005 and ceased in the year 2015, it was not considered. Based on the authors experience and discussions with experts with local knowledge in each jurisdiction, no notable irrigation developments commenced after 1999 and ceased before 2023. This is likely to be due to the considerable initial capital outlay for an irrigation development; approximately \$6,000–\$12,000/ha for broadacre cropping and \$25,000–\$75,000/ha for horticultural developments, excluding the costs of providing the water (Stokes et al. 2023).

In addition to the ALUMC land use code, the commodity being grown was also recorded where it had been publicly reported (e.g. media reporting) or known to government extension officers. Commodities recorded include avocado, African mahogany, banana, black wattle, cotton, dates, forage sorghum, grapefruit, limes, mangoes, melon, oranges, Rhodes grass hay, sandalwood, chia and watermelon

As well as land use, the irrigation water source and the irrigation application method were attributed where this information could be determined from the satellite imagery, publicly available information or expert knowledge. Water source was categorised as either a) surface water (gully dam, ring tank, direct river pumping or irrigation scheme supplied water) or b) groundwater bores. Irrigation systems were categorised as a) microsystems (trickle tape and

micro-sprinklers), b) overhead systems (centre pivot, lateral movers and spray guns), c) surface systems (furrow and flood), or d) unknown.

Land use polygons were also attributed with the state or territory jurisdiction, the river catchment (AWRC, 1997) and key region (Table 1).

Irrigated cropping and horticulture areas within the most eastern part of the Mitchell catchment (Qld) and part of the ‘Mareeba – Dimbulah Water Supply Scheme’ (MDWSS) were not recorded because the water source for this irrigation is from the Barron River, which is a catchment that flows into the Great Barrier Reef Lagoon, eastern Qld. Eastern Qld, and is outside the study area.

Cropping, horticulture and plantation forestry land uses were compared to four covariates, a) mean annual rainfall (MAR); b) soil type; c) land tenure; and d) remoteness — to determine if there were any relationships with enterprise location (Table 2). Note that these four covariates are not independent. For example, land tenure is strongly associated with soil type and rainfall. This lack of independence complicates interpretation of relationships, as effects cannot be readily separated. Given these interdependencies, and because our objective was descriptive rather than inferential, the results are presented as an exploratory analysis rather than applying formal statistical tests.

208 Table 2 Ancillary spatial data

Name	Source	Description	Reference
Mean annual rainfall	Australian Bureau of Meteorology	Spatial grid of mean annual rainfall for Australia based on 1981 - 2010 rainfall data. Data to the nearest whole number.	(Bureau of Meteorology, 2024)
Soil order	Terrestrial Ecosystem Research Network	Spatial grid of soil orders for Australia that represents the ‘highest level classification’ in the Australian Soil Classification (Isbell and National Committee on Soil and Terrain, 2021). Data contains 14 classes.	(Searle, 2021)
Land tenure	Australian Bureau of Agricultural and Resource Economics and Sciences	Spatial grid of land tenure for Australia based on 2015 - 2016 data. 19 land tenure types are mapped of which nine intersect with irrigated or rainfed land uses in INA.	(ABARES, 2021b)
Remoteness		Spatial grid of remoteness that maps remoteness based on distance to nearest service centre. Remoteness ranges from 0 (located within a service centre) to 15 (three times the mean remoteness of the whole dataset). INA data range 1.6 to 10.8; Mean 6.25; Median 6.1	(Markham, 2016)

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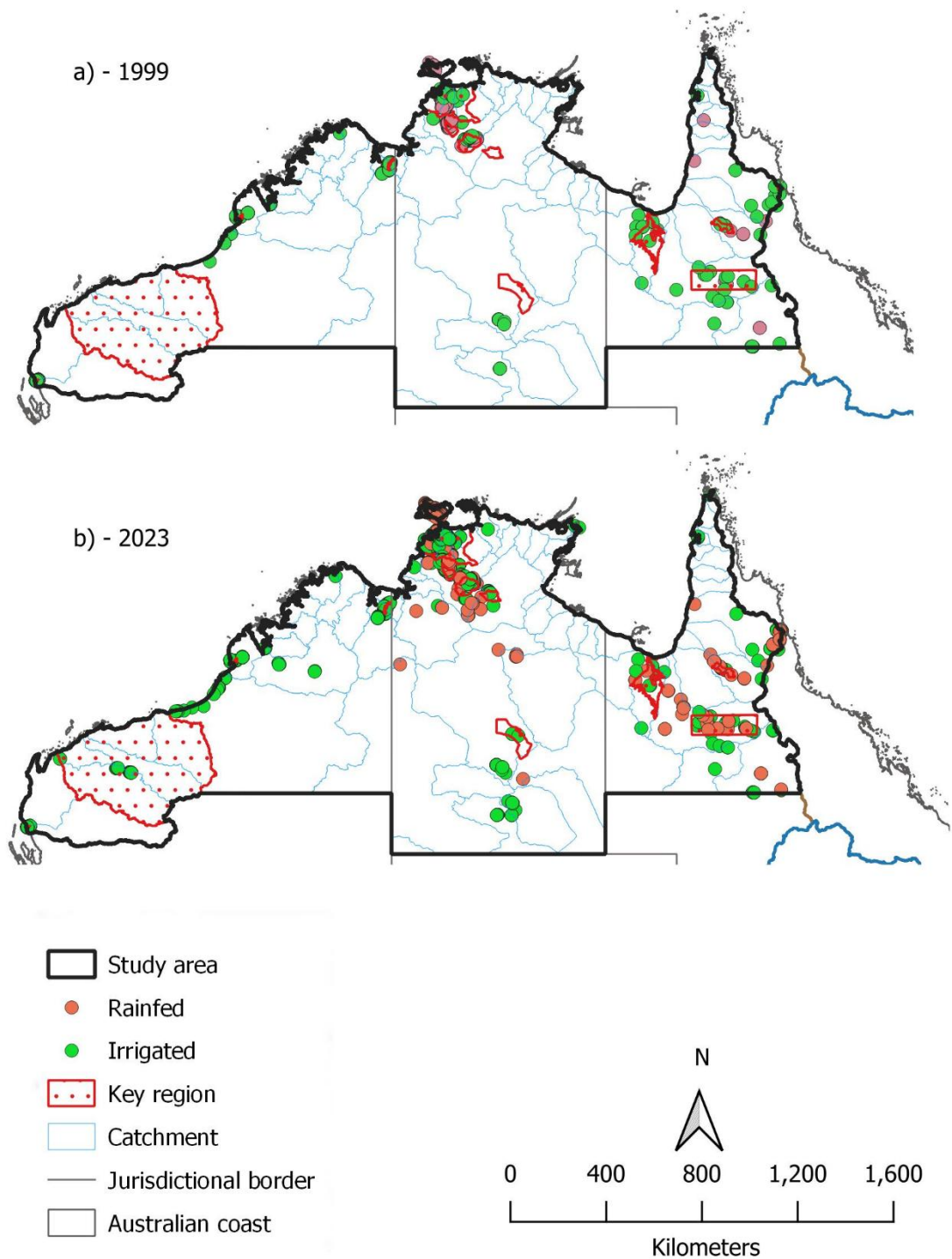
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3. Results

In 2023, irrigated (60,303 ha) and rainfed agriculture and plantation forestry (134,362 ha) across INA (308,414,465 ha) occupied a relatively small proportion of the study area, 0.02% and 0.04% respectively (Table 3).

Of the total irrigated area in 2023, 48% was in WA, 39% in the NT and 13% in QLD. In northern WA, of the 28,718 ha of irrigated agriculture, 73% occurs in the irrigation schemes of the Ord River Irrigation Area (ORIA) (68%) and Carnarvon Irrigation District (CID, 5%). In the NT, while irrigation is patchy or ‘mosaic’ in nature it predominantly occurs around several geographic centres, namely the Darwin Rural Area (29% of the 23,641 ha), Katherine (28%) and Douglas-Daly (16%). In inland Qld irrigated agriculture is also in a mosaic form, however irrigation enterprises are widely disbursed (Figure 2).

The 13 key regions listed in Table 1 contained 81% (48,606 ha) of the irrigated land and 38% (51,218 ha) of rainfed agriculture and plantation forestry across INA in 2023. The majority of rainfed cropping and plantation forestry in INA occurs in the NT (80%), with no rainfed cropping or plantation forestry recorded occurring in that part of WA within the study area in 2023.



228

229 Figure 2 Irrigated and rainfed cropping, horticulture and plantation forestry in a) 1999 and b) 2023. Symbols are
230 exaggerated in size for display purposes.

3.1 Change in areas of irrigation and rainfed cropping and plantation forestry from 1999 to 2023

In 1999 irrigated land across INA occupied 32,904 ha or 0.01% of the study area. By 2023, this had increased to 60,303 ha or 0.02% of the study area. This equates to a net increase in irrigated land of 1,141 ha per year over 24 years across INA, noting that change in irrigated and rainfed land does not occur uniformly through time. Northern WA (i.e. the ORIA) had the largest net annual rate of change (i.e. +536 ha per year) of the three jurisdictions. The area of rainfed cropping and plantation forestry increased from 28,811 ha or 0.01% of the study area in 1999 to 134,362 ha or 0.04% of the study area in 2023. This equates to a net increase in rainfed land of 4,394 ha per year over 24 years and is nearly four times that of irrigated cropping, horticulture and plantation forestry (Table 3). The majority (77%) of the increase occurred in the NT with the remaining 23% occurring in inland Qld. Northern WA did not have any rainfed cropping, rainfed horticulture or rainfed plantation forestry recorded within the study area in 1999 or 2023.

For the purposes of this study INA was disaggregated into 77 catchment based reporting units. Of these 23 (30 %) had irrigated land in 1999 and 31 (40 %) reporting units recorded irrigation in 2023. Nine (12 %) reporting units had rainfed cropping and plantation forestry in 1999 and 17 (22 %) reporting units recorded rainfed cropping and plantation forestry in 2023 (Supplementary Table 1).

3.2 Source of irrigation water and types of water application technology

Approximately 48% of the irrigated land across INA in 2023 sourced irrigation water from rivers, creeks and dams (i.e. surface water) and 46% sourced water from groundwater (6% unknown), however, the proportions strongly differed between the jurisdictions (Supplementary Table 2).

Table 3 Irrigated and rainfed cropping, horticulture and forestry in the study area, in 2023 and 1999, analysed by jurisdictions and key regions as well as the whole of inland northern Australia

Reporting unit	Extent	Irrigated land area			Rainfed land area		
		1999	2023	Annualised change	1999	2023	Mean annual change
Units	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)
Inland northern Australia	308,414,465	32,904	60,303	+1141	28,811	134,362	+4398
Inland northern Australia split between jurisdictions							
Northern Western Australia	107,160,110	15,847	28,718	+536	0	0	0
Northern Territory	134,198,174	12,160	23,641	+478	25,904	107,646	+3406
Inland Queensland	67,056,181	4,897	7,944	+127	2,907	26,716	+992
Key regions in northern Australia							
Carnarvon Irrigation District (WA)	4,000	1,332	1,365	+2	0	0	0
Pilbara Hinterland Ag Dev Initiative* (WA)	24,026,623	0	1,859	+77	0	0	0
Skuthorpe (Broome) (WA)	21,200	111	247	+6	0	0	0
Ord River Irrigation Area (WA)	21,400	13,066	19,651	+274	0	0	0
Western Davenport - Central Plain (NT)	1,042,200	0	863	+36	0	0	0
Mataranka Region (NT)	551,358	0	2,239	+93	0	0	0
Katherine Region (NT)	595,114	4,267	6,604	+97	4022	10,355	+264
Douglas-Daly Area (NT)	206,176	246	3,870	+151	9,273	15,428	+256
Darwin Region (NT)	696,400	6,594	6,964	+15	3,122	12,875	+406
Armynald Plain (QLD)	1,294,400	998	1,614	+25	0	4,268	+178
Upper Flinders (QLD)	5,485,850	243	1,361	+47	32	7,551	+313
Gilbert River Agricultural Project (QLD)	252,100	381	473	+4	444	668	+9
Julatten (QLD)	12,100	1,511	1,496	-1	73	73	0

Footnotes: *Expansion in the Pilbara Hinterland Agricultural Development Initiative area is mostly due to mine dewatering activities.

In northern WA and inland Qld, 83% and 58% of land was irrigated using surface water respectively (noting that 22% of the water source in inland Qld was unknown), while in the NT only 5% of the irrigated area was irrigated with surface water. Excluding the ORIA, 7% of the remaining irrigated land in northern WA used surface water. Most of the land irrigated using surface water in inland Qld used off-stream storages to store the water (85%). Recycled water from town water treatment plants is also a source of water used to irrigated pastures in some small areas (Pedersen *et al.*, 2018). In the Fortescue catchment in the Pilbara (WA), water from mine dewatering activities irrigated up to 1,757 ha of land for fodder crops.

The most common irrigation application systems in INA are surface systems, used on at least 40% of the land under irrigation. Surface irrigation systems are the primary irrigation water application method in Qld (64%), whereas it is predominantly micro systems in the NT (73%). Northern WA has the most diverse types of irrigation systems, with surface systems used exclusively in the ORIA (furrow) while elsewhere water for overhead and micro systems is sourced from groundwater (Supplementary Table 3).

3.3 Key agricultural commodities grown in INA during 2023

Sandalwood plantations (19%), broadacre cotton (13%), mango orchards (13%) and vegetables and other seasonal horticulture (12%) made up the majority (57%) of the irrigated cropping, horticulture and plantation forestry in INA. Sandalwood plantations were restricted to the Daly (NT) and Ord (WA) catchments and are grown to produce sandalwood oil for pharmaceutical, ceremonial and fragrance markets worldwide. (Table 4).

Table 4 Irrigated land uses in inland northern Australia in 2023 presented by jurisdiction

Irrigated land use	Commodity	Inland northern Australia split between jurisdictions			
		Northern Western Australia	Northern Territory	Inland Queensland	Inland Northern Australia
		(ha)	(ha)	(ha)	(ha)
Hardwood plantations	Sandalwood	6,445	5,271	0	11,716
Plantation forests	Undefined	168	7	17	192
Modified pastures		1,809	562	130	2,501
Silage and hay	Forage	1,178	813	877	2,868
	sorghum				
	Rhodes grass	2,169	629	1,194	3,992
	hay				
Cereals	Sorghum	466	67	0	533
Cotton		3,042	1,412	3,223	7,677
Oilseed	Chia	4,803	0	0	4,803
Rice		0	284	0	284
Sugar		0	0	1,363*	1,363
Cropping	Undefined	646	380	452	1,478
Tree fruits	Mangoes	970	6,350	242	7,562
	Bananas	419	7	6	432
	Avocados	18	0	0	18
	Dates	0	27	0	27
	Undefined	436	636	44	1,116
Citrus		23	137	0	160
Grapes		266	287	165	718
Perennial horticulture	Undefined	275	164	73	512
Seasonal fruits	Melons	233	2,936	0	3,169
Seasonal vegetables & herbs		4,216	1,419	0	5,635
Seasonal horticulture	Undefined	1,092	622	2	1,716
Other cropping, horticulture & plantations	Undefined	44	1,631	156	1,831
Total		28,718	23,641	7,944	60,303

Table footnote: *Mostly in the Julatten area of the Mitchell catchment.

285 Irrigated mangoes are a long-established orchard crop located mostly near Darwin and
 286 Katherine but also grown in the ORIA (WA), Mataranka (NT), the Gilbert River Agricultural
 287 Precinct (Qld), the CID (WA) and at Skuthorpe (WA). Bananas are one of the main crops for
 288 the (CID) and are also grown in the ORIA in WA. Vegetables are grown mostly in the ORIA
 289 but also near Darwin and in the CID, Skuthorpe (Broome) and on isolated farms in the Great
 290 Sandy Desert region of WA. Rhodes grass hay (7% of the irrigated land use in INA) is grown
 291 throughout INA. Chia oilseed (8% of the irrigated land use in INA) is well established in the
 292 ORIA. Melons (5% of the irrigated land use in INA) are mainly grown in the NT at
 293 Mataranka, Katherine and Western Davenport. Rice was trialled in the Fitzroy River
 294 catchment (WA) but now is only grown around Darwin within a small area (Table 5).

295 Forage sorghum (53%) and forestry plantations (35%) made up most of the rainfed cropping,
 296 horticulture and plantation forestry in INA (Table 6). Rainfed forage sorghum and Rhodes
 297 grass hay (2%) production are used to supplement and finish local beef cattle for market. Hay
 298 is also exported overseas. The catchments with the largest areas of rainfed broadacre
 299 cropping were the Daly, NT (36,216 ha) and the Flinders Qld (17,798 ha) catchments
 300 (Supplementary Table 1).

301 Nearly all rainfed plantation forestry occurs on Melville Island (Tiwi Islands, NT) as black
 302 wattle hardwood plantations, trees are chipped for paper pulp. African Mahogany hardwood
 303 plantations are grown in the Daly catchment for sawn timber for flooring, furniture or veneers
 304 (Supplementary Table 4).

305 Table 5 Irrigated land uses in inland northern Australia in 2023, presented by key region

Irrigated land use	Commodity	Northern Western Australia					Northern Territory				Inland Queensland			
		Carnarvon	Pilbara	Skuthorpe	Ord River	Western	Mataranka	Katherine	Douglas	Darwin	Armraynald	Upper	Gilbert	Julatten
		Irrigation	Hinterland	(Broome)	Irrigation	Davenport	Region	Region	-Daly	Rural	Plain	Flinders	River	
		District	Ag Dev		Area	- Central			Area	Area			Agricultu	
			Initiative			Plain							ral	Precinct
		(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)
Hardwood	Sandalwood	7	0	0	4,317	0	0	2,352	2,919	0	0	0	0	0
plantations														
Plantation	Undefined	0	0	0	168	0	0	5	0	2	0	0	0	0
forests														
Modified		0	317	6	349	0	0	257	0	36	0	63	0	0
pastures														
Silage and	Forage	0	927	0	170	126	0	267	94	0	0	713	164	0
hay	sorghum													
	Rhodes grass	0	615	145	0	0	0	91	0	0	444	377	0	63
	hay													
Cereals	Sorghum	0	0	0	465	0	0	44	0	0	0	0	0	0
Sugar		0	0	0	0	0	0	0	0	0	0	0	0	1,363
Cotton		0	0	0	3,042	0	0	0	657	0	1,170	0	0	0

Irrigated land use	Commodity	Northern Western Australia					Northern Territory					Inland Queensland		
		Carnarvon	Pilbara	Skuthorpe	Ord River	Western	Mataranka	Katherine	Douglas	Darwin	Armraynald	Upper	Gilbert	Julatten
		Irrigation	Hinterland	(Broome)	Irrigation	Davenport	Region	Region	-Daly	Rural	Plain	Flinders	River	
		District	Ag Dev		Area	- Central			Area	Area			Agricultu	
			Initiative			Plain							ral	Precinct
Oilseed		0	0	0	4,803	0	0	0	0	0	0	0	0	0
Rice		0	0	0	0	0	0	0	0	284	0	0	0	0
Cropping	Undefined	1	0	0	597	0	0	0	0	0	0	25	0	0
Tree fruits	Mangoes	197	0	63	682	0	322	1,753	0	4,174	0	0	210	3
	Bananas	302	0	0	114	0	0	2	0	5	0	0	0	6
	Avocadoes	18	0	0	0	0	0	0	0	0	0	0	0	0
	Undefined	20	0	5	409	0	0	98	0	449	0	7	28	0
Citrus		17	0	0	5	0	0	63	0	72	0	0	0	0
Grapes		190	0	0	75	0	0	0	0	0	0	165	0	0
Perennial horticulture	Undefined	0	0	0	275	0	0	71	0	57	0	9	0	61
Seasonal fruits	Melons	6	0	0	74	579	1,067	787	200	303	0	0	0	0

Irrigated land use	Commodity	Northern Western Australia					Northern Territory					Inland Queensland		
		Carnarvon	Pilbara	Skuthorpe	Ord River	Western	Mataranka	Katherine	Douglas	Darwin	Armraynald	Upper	Gilbert	Julatten
		Irrigation	Hinterland	(Broome)	Irrigation	Davenport	Region	Region	-Daly	Rural	Plain	Flinders	River	
		District	Ag Dev		Area	- Central			Area	Area			Agricultu	
			Initiative			Plain							ral	Precinct
Seasonal		604	0	28	3,007	158	0	126	0	911	0	0	0	0
vegetables &														
herbs														
Seasonal	Undefined	0	0	0	1,058	0	0	60	0	562	0	2	0	0
horticulture														
Other cropping, horticulture &		3	0	0	41	0	850	628	0	109	0	0	71	0
plantations														
Total		1,365	1,859	247	19,651	863	2,239	6,604	3,870	6,964	1,614	1,361	473	1,496

306

307

308

Table 6 Rainfed land uses in inland northern Australia in 2023 presented by jurisdiction

Rainfed land use	Commodity	Inland northern Australia split between jurisdictions			
		Northern Western Australia (ha)	Northern Territory (na)	Inland Queensland (na)	Inland Northern Australia (na)
Hardwood plantation	African mahogany	0	14,433	0	14,433
Pulp wood plantation	Acacia mangium	0	31,766*	0	31,766
Plantation forests	Undefined	0	1,285	110	1,395
Hay & silage	Forage sorghum	0	57,329	14,140	71,469
	Rhodes Grass hay	0	225	2,813	3,038
Cereals	Sorghum	0	45	5,345	5,390
Cotton		0	2,443	3,620	6,063
Cropping	Undefined	0	5	557	562
Perennial horticulture		0	91	131	222
Other cropping, horticulture & plantations	Undefined	0	24	0	24
Total		0	107,646	26,716	134,362

3.4 Mean annual rainfall, soil type, land tenure and remoteness and the location of cropping, horticulture and plantation forestry in INA

Figure 3 shows that rainfed plantation forestry occurs in areas with a higher MAR than the other land uses, though most of these plantations are black wattle plantations on Melville Island north of Darwin. Rainfed cropping has a similar median MAR to irrigated cropping. There are few observations for rainfed perennial and seasonal horticulture as expected given the long dry season in INA making rainfed horticulture unviable. Irrigated pastures appear to occur in the drier parts of INA and are probably a feed supplement for the cattle industry or for the live cattle export trade. Except for rainfed seasonal horticulture, the MAR data have a wide range.

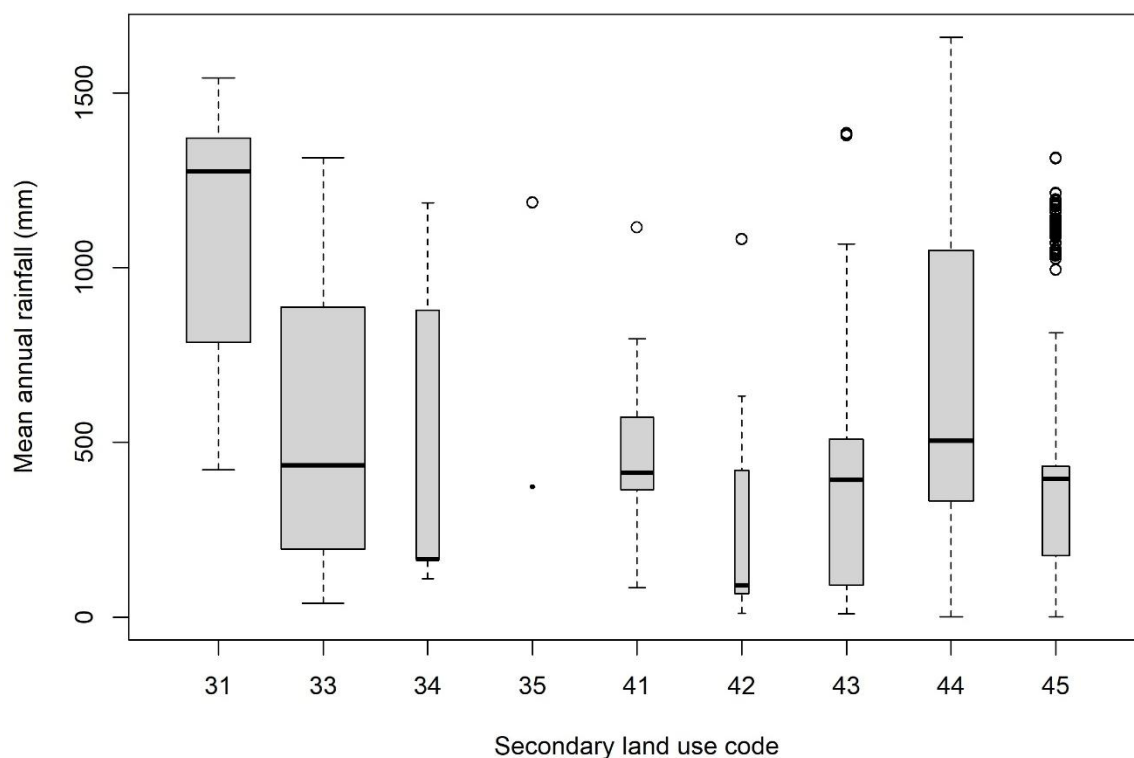


Figure 3 Box plots of land use (grouped according to secondary level land use classifications) compared to mean annual rainfall in inland northern Australia. The width of the boxplots is proportional to the area for each land use. Secondary land use codes; 31 - Rainfed plantation forest; 33 – Rainfed cropping; 34 – Rainfed perennial horticulture; 35 – Rainfed seasonal horticulture; 41 – Irrigated plantation forest; 42 – Irrigated modified pastures; 43 – Irrigated cropping; 44 – Irrigated perennial horticulture; 45 – Irrigated seasonal horticulture.

Figure 4 shows that the majority of irrigated and rainfed agriculture in INA occurred on Kandosols (60%) and Vertosols (29%). This weakly mirrors the pattern of soil distribution across the INA (Kandosols (43%), Tenosols (21%) and Vertosols (14%)).

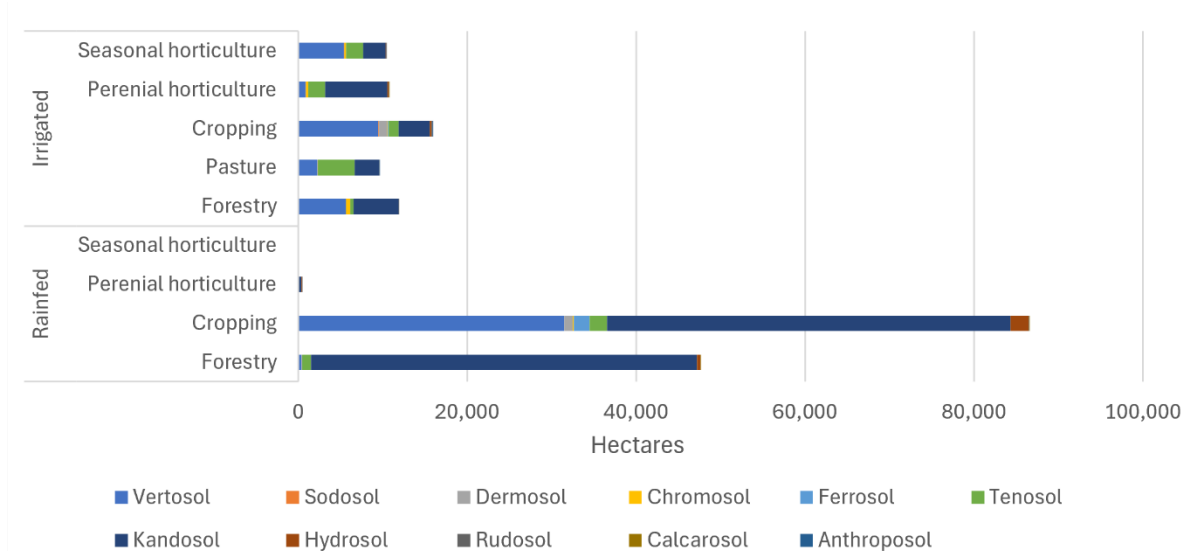


Figure 4 Irrigated and rainfed land use (grouped according to secondary level land use class) compared to area of soil type (Soil Orders, Australian Soil Classification) for inland northern Australia.

The two main types of land tenure most relevant to agriculture in INA are leasehold title of Crown land (58%) and freehold (privately owned land) (25%). The most common leasehold title are pastoral leases primarily for grazing cattle. Pastoral lease types and lease conditions vary across the three jurisdictions but in many areas, it is difficult to obtain regulatory approval for cropping, especially if the cropping enterprise is predominantly aimed at producing more than forages and hay for cattle. Most of the horticulture and plantation forestry (95 %) occurred on freehold title. Excluding the ORIA and the CID, which are government sponsored freehold schemes, 94 % of horticulture and plantation forestry occurred on freehold title, 41% of this freehold land has Aboriginal freehold title.

A small proportion of irrigated horticulture (4 %) occurred on Aboriginal freehold lands that were former Aboriginal reserves converted to freehold title under the Aboriginal Land Rights (NT) Act 1976. This land is held by Aboriginal Land Trusts and cannot be sold (NTG, 2024) but some has been leased for agricultural production to interests that are not Indigenous.

Almost 32,000 ha of Aboriginal freehold land is used by Traditional Owners on the Tiwi islands for plantation forestry. This represents almost 24% of the total area of rainfed

agriculture in the study area and 24% of the increase in rainfed cropping across INA between 1999 and 2023.

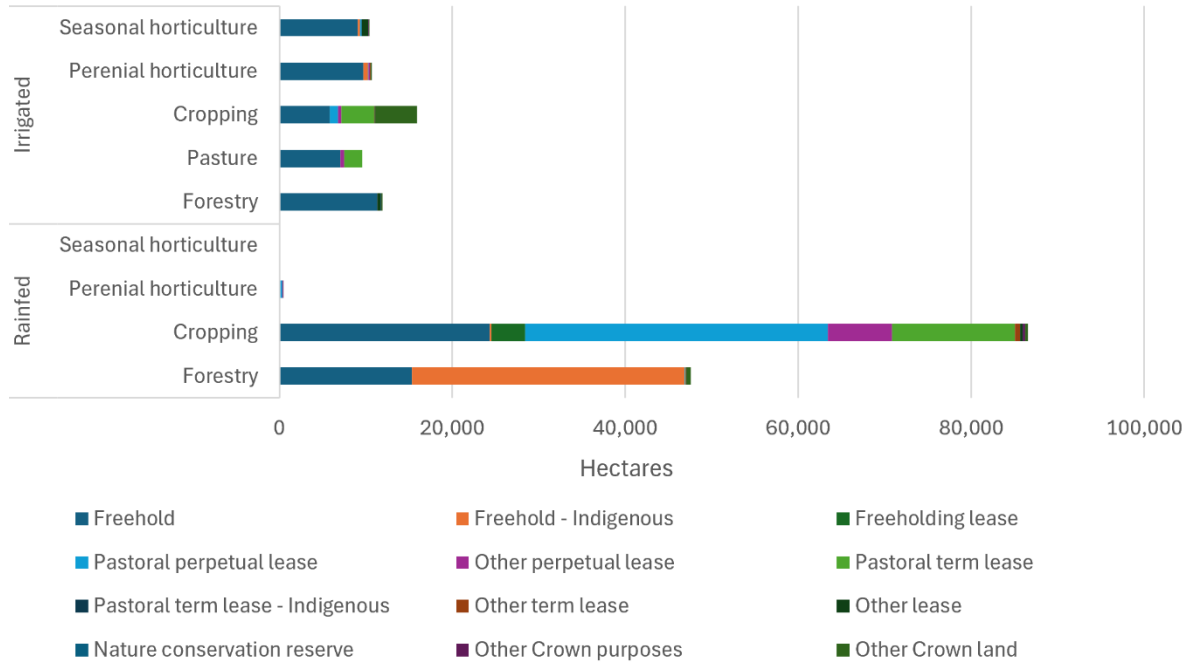


Figure 5 Irrigated and Rainfed land use (grouped according to secondary level land use classifications) compared to the land tenure in inland northern Australia.

The compiled land tenure data (2015) may be out of step with land use in 2023 in a few, small areas of leasehold land that may now have freehold title.

The remoteness index shown in Figure 6 (remoteness from nearest service centre) can range from zero (located within a service centre) to 15 (two and half times the median remoteness (6.1) of the whole dataset (Markham, 2016)). Rainfed cropping has a very narrow range of data.

Irrigated plantation forestry, irrigated modified pastures, cropping and seasonal horticulture all occur in more remote areas than rainfed land uses and irrigated horticulture. These remote land uses include irrigated sandalwood in the Ord catchment (WA); forage sorghum in the Great Sandy Desert area, Cape Leveque and Fitzroy catchment (WA) and Barkly and Wiso

catchments (NT); sweet corn and melons in the Great Sandy Desert area (WA); vegetable and mangoes in the Skuthorpe region (WA); and table grapes in the Wiso catchment (NT). Irrigated modified pastures such as Rhodes grass for grazing and hay production is grown in the remotest parts of the INA over a wide range of remoteness. Mango orchards in the NT are in the less remote regions of northern NT.

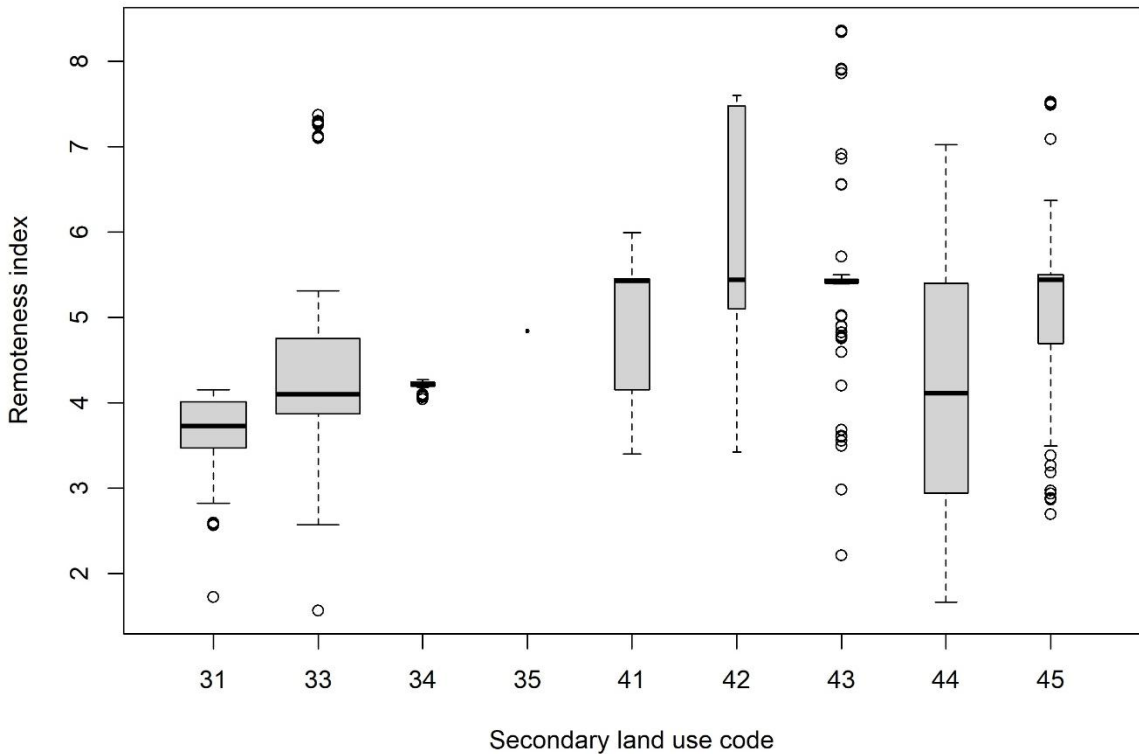


Figure 6 Boxplot of land use (grouped according to secondary level land use classifications) compared to remoteness for NA. Remoteness is a measure between 0 (in town) and 15 (very remote). The median for inland northern Australia is 6.1. The width of the box plot is proportional to the number of observations. Secondary land use codes; 31 - Rainfed plantation forest; 33 - Rainfed cropping; 34 - Rainfed perennial horticulture; 35 - Rainfed seasonal horticulture; 41 - Irrigated plantation forest; 42 - Irrigated modified pastures; 43 - Irrigated cropping; 44 - Irrigated perennial horticulture; 45 - Irrigated seasonal horticulture.

4. Discussion

4.1 Irrigation development in INA in a national and global context

The total area of irrigated agriculture across INA in 2023 was 60,303 ha, which is about 0.02% of the area. Petheram et al., (2018a) estimated 1.84 Mha would be physically possible to irrigate across INA based on soil and water alone. While the absolute increase in irrigated areas across INA is relatively small (27,399 ha over 24 years), in percentage terms irrigated area increased by 83% across INA between 1999 and 2023. As outlined below this is significantly higher levels of percentage growth than observed at national and global scales, as well as coastal north Qld.

Globally the expansion of arable land has been relatively modest. Fischer, (2016) reported an increase in arable land of only about 10% while the FAO (2023) reported an increase in cropped area of 6% between 2000 and 2021. Both authors, however, reported a greater rate of expansion of area of irrigation than rainfed cropping, with FAO (2023) estimating a 20% increase in land ‘equipped’ for irrigation between 2000 and 2021, thus highlighting a global trend of agricultural intensification. Future projections for global arable land in 2050 range from 300 to 800 million ha (Puy, Lo Piano and Saltelli, 2020), with the authors warning that globally the area under irrigation is likely to grow more than previously thought.

Based on data supplied by the Australian Bureau of Statistics, at the national level, a similar trend was observed. In recent decades agricultural output growth in Australia has primarily been driven by productivity improvements rather than an expansion of irrigated land (Productivity Commission, 2005). Between 2002–03 and 2020–21, the total irrigated area in Australia declined from 2.4 million ha to 1.9 million ha, of which 1.2 million ha was in the MDB (ABS, 2022). However, irrigation developments across Australia, particularly in the MDB, are rarely fully utilised in any given year. The total irrigated area fluctuates

significantly due to factors such as rainfall timing, supplementary irrigation requirements, and variations in water allocations determined by reservoir storage, rainfall, and state water-sharing plans. For instance, between 2005–06 (ABS, 2008a) and 2006–07 (ABS, 2008b), the total irrigated area in Australia declined by 25%, from 2,546,000 ha to 1,923,000 ha, with mean annual water application rates also decreasing from 4.2 ML/ha to 4.0 ML/ha. These fluctuations, along with genetic advances and changes in commodity prices, influence crop selection, as observed in the MDB, where rice production has declined while higher value fruit and nut production has increased.

In north-eastern coastal Qld, this study calculated from existing Qld Government (QLUMP, 2023) mapping that the irrigated area expanded from 384,431 ha in 1999 to 397,912 ha in 2021, an increase of 3.5% (13,481 ha). During the same period, rainfed agricultural areas decreased 7.3% (40,602 ha), from 557,462 ha to 516,859 ha. The continued expansion of the area under irrigation across the much smaller north-eastern coastal Qld region is likely due to factors such as the availability of unallocated water within existing supply schemes (Petheram *et al.*, 2014), proximity to established town and community infrastructure, access to specialised agricultural expertise and services, profitability and differences in land tenure and Native Title considerations compared to pastoral leasehold land in INA. Additionally, regulatory and logistical constraints associated with expansion of existing irrigation developments may have been more effectively managed in regions with long-established irrigation practices.

Northern Australia was once touted as having the potential to become the ‘food bowl’ of Asia (e.g. Turton 2025). Petheram *et al.* (2014, 2018a) dismissed this notion based on analyses of the coincidence of land and water resources across the north. At approximately 60,000 ha and at the current rate of expansion (mean rate of 1,141 ha per year over a 24 year period) this

study further supports the notion that the irrigated land of INA is unlikely to become Asia's 'food bowl' in the near future, especially when compared to the nearly 2,000,000 ha of irrigated land in the MDB and the nearly 400,000 ha in north-eastern coastal Qld. Even if the amount of irrigated land in INA reached 100,000 ha the food grown (assuming no fibre or wood production) would only support approximately 1 – 3 million people, considerably less than Asia's net annual population growth of ~45 million people, and a small fraction (~0.04 %) of the nearly 5 billion people in Asia (WPC 2026).

4.2 Cropping distribution in INA and its drivers

The location of irrigated agricultural areas is influenced by land tenure, particularly freehold land title (Figure 5), but also access to relatively inexpensive water, structured water planning, and defined water entitlements. The Great Sandy Desert, Darwin Rural Area, and Katherine area primarily rely on groundwater, often one of the more cost-effective water sources. While groundwater systems are widespread across INA, high-yielding sandstone aquifers in the Great Sandy Desert and the Tindal carbonate aquifer in the Katherine region are particularly productive, with water bearing formations at economically viable depths for drilling.

The ORIA and irrigation developments in the Flinders catchment primarily depend on surface water. The ORIA is INA's largest irrigation development, with over \$1.5 billion invested by the Australian and Western Australian governments (Grudnoff and Campbell, 2017). This investment is effectively a 'sunk cost,' as water charges paid by farmers to the Ord River Cooperative only cover operational expenses. As a result, the Kununurra Diversion Dam (constructed in 1962) and the Ord River Dam (constructed in 1972) provide high-reliability irrigation water at significantly lower costs (~\$400/ha) than comparable supply schemes in north-eastern coastal Qld and the MDB.

In the NT, irrigation development has almost exclusively relied on groundwater due to the presence of productive carbonate/dolostone aquifers underlying productive red kandosol soils. In the Flinders catchment in Qld, characterised by extensive alluvial and treeless cracking clay soils (Bartley *et al.*, 2013), irrigation development typically involves water harvesting—pumping or diverting river water into enclosed earth embankment storages (ring tanks) adjacent to the river. Under favourable conditions, this approach can be cost-effective (Petheram *et al.*, 2015). Notably, the Flinders catchment has a long history of advocacy for dam and irrigation development as a strategy to counter regional population decline (Petheram *et al.* 2013; McKellar *et al.*, 2015). This history has fostered strong local support for irrigation expansion. It should be noted, however, unlike other INA regions, many Traditional Owners from the Flinders catchment have been displaced due to historical processes and now primarily reside in urban centres such as Brisbane, Townsville, and Cairns (Barber, 2013).

4.3 How might the area of cropping across INA change in the future?

The National Farmers' Federation (NFF) of Australia set an ambitious target to achieve \$100 billion in gross value of agricultural production by 2030 (NFF, 2019), necessitating about a 40% increase from levels reported in 2016-17 when the target was set. To contribute to this goal, irrigated agriculture must either transition to higher-value commodities in water-scarce regions or expand into other areas with perceived water availability. Despite aspirational targets substantial increases in agricultural production in Australia will only occur under favourable market settings.

While key drivers of food demand in Australia includes population growth, shifts in consumer preferences, and income growth (Hogan, 2018), typically about 65% of Australia's agricultural production is exported (DFAT, 2017). As a result, national food security does not drive agricultural expansion in Australia; rather, the feasibility of increasing irrigated areas

depends on favourable export conditions, particularly competitive commodity prices and reliable markets and sustained global demand. It should be noted, however, that industry argue that agricultural exports help ensure national food security by underpinning sustainability at the farm level as well as regional communities (House of Representatives, 2023). Given the constraints on expansion in the MDB due to water over-allocation, projected declines in rainfall (Whetton and Chiew, 2021), and water reforms designed to drive agricultural water use to its highest value and enable water recovery for the environmental and cultural purposes (Grafton and Wheeler, 2018), private investment in irrigation infrastructure is increasingly shifting focus not just towards INA but also other regions with perceived water surpluses, such as Tasmania (Kirby 2020) This pattern is also reflected in foreign ownership with the NT (27.6%) and Tasmania (23.9%) having the largest proportions of farmland under foreign ownership (McLennan, 2025). Both jurisdictions only had about 10% foreign ownership in the year 2000.

This study suggests that irrigation development is most likely to occur in locations with enabling infrastructure, where water is most cost-effective, close to soils suitable for agricultural development on freehold land, and in regions with established government water plans that have reconciled diverse public opinions, including Indigenous perspectives.

Agricultural skills and capability are also required, but these can be brought in from elsewhere. Success is more likely in greenfield areas when development is staged to allow learning at a smaller scale before proceeding to full development (Stokes et al. 2017).

4.3.1 Irrigated fodder and the beef industry in INA

The beef industry is the longest continuously operating agricultural sector in INA, and there has been ongoing interest in integrating irrigated agriculture to enhance profitability and mitigate risk associated with the live export market. However, only a limited number of the

approximately 700 pastoral stations across INA have experimented with irrigated fodder and pasture cropping and fewer still have persisted (Grice and Watson, 2013). This is reflected in this study, which found only 16% of land irrigated in 2023 was under silage, hay or modified pastures (Table 4). In different parts of INA motivations vary but most stations are primarily interested in irrigated fodders and pastures to increase animal weight (and thereby sale at a younger age) and increased weaning rate (MacLeod *et al.*, 2013). Despite this interest, desktop analyses indicate that, under historical beef prices, incorporating irrigated fodder or pasture crops into an existing beef enterprise does not enhance enterprise profitability when capital and operating costs are considered (MacLeod *et al.*, 2018), except under high beef price and low capital cost scenarios (Watson *et al.* 2025). However, these high beef prices must be sustained over the majority of the investment period - yet historically sustained high beef prices have been uncommon. Alternative investments, such as sub-division of large paddocks or additional investments in station infrastructure may provide better use of capital investment for production and financial gains (MacLeod *et al.*, 2018). Unless significant structural changes occur in beef markets—resulting in sustained price increases or disruptions to live export markets necessitating heavier cattle production or local finishing —widespread adoption of locally grown irrigated fodder and pastures on pastoral stations in INA remains unlikely. Even so, irrigated forage or hay production in the order of only hundreds to one or two thousand hectares would be required to meet the needs of most stations across INA, depending on enterprise type.

4.3.2 Horticultural expansion across INA

Horticultural production in INA is limited by market constraints and price volatility caused by fluctuations in supply and demand (Ash *et al.*, 2014). Successful operations have relied on competitive advantages, such as climate conditions allowing producers to meet niche market

demands and cost-effective backloading transportation to more populous areas in southern Australia. Large-scale expansion of horticulture would require the development of supporting infrastructure (e.g. cold stores and all-weather roads), large seasonal labour pools and reliable export markets, particularly for horticultural tree crops that have long establishment times. Even with the advent of new export markets, producers would face competition to maintain access to those markets from other tropical agricultural regions, particularly those undergoing large increases in cropped area, such as Indonesia (49% increase in cropped area between 2000 and 2021), Brazil (20% between 2000 and 2021), and Nigeria (7% between 2000 and 2021) (FAO, 2023). If horticultural produce in INA were to substantially increase, focusing on produce with lower labour requirements may lower risk. On balance, these factors suggest that expansion of horticultural enterprises in INA is more likely than not to remain a niche opportunity in the short-to-medium term.

4.3.3 Broadacre cropping in INA

Across INA, the area under irrigated cotton is more than the area under all other broadacre crops combined (Table 4). Except for cotton, substantial expansion of irrigated broadacre cropping across INA appears unlikely. The real prices of staple broadacre crops such as wheat, rice, and maize have remained stagnant or declined since the 1960s (Fischer, 2016). Given that broadacre cropping in INA is not commercially viable where domestic transport distances are required (Ash *et al.*, 2014; Stokes *et al.*, 2017), it is improbable that this situation will change in the foreseeable future. An exception is irrigated and potentially rainfed cotton, which is expected to expand significantly. Historically, the lack of cotton processing plants within economic transport range has hindered commercial cotton production in INA, as a minimum viable irrigated area of approximately 7,500 ha, depending upon yields and the reliability of water supply, is required for a processing plant (Ash *et al.*, 2014; ABC, 2019).

However, in recent years sustained high cotton prices have enabled farmers to transport raw cotton from INA to processing plants in Emerald, Qld. This in turn has demonstrated the viability of cotton to be commercially grown in parts of INA, creating sufficient momentum for a cotton processing plant to be constructed in Katherine (NT) in 2023 and Kununurra (WA) in 2025 (Cotton Australia 2025). These facilities can reportedly each support up to 15,000 ha of irrigated cotton (ABC, 2023; KDC, 2024).

With cotton being the crop most likely to drive a significant expansion in irrigated agriculture across INA, irrigated and rainfed development over the next 5 to 10 years is expected to primarily be concentrated within a 50 to 100 km radius of the recently established cotton processing plants. Further expansion of irrigated cotton in these areas will primarily depend on additional water allocations rather than limitations in processing capacity. The time required to finalise surface water management plans is a constraint on the pace of irrigation expansion. As no formal surface water plans currently exist in the NT, the development and implementation of such frameworks are likely to be protracted. While rainfed cotton close to these processing plants may see rapid initial expansion due to its relatively low setup costs, rainfed cotton production is expected to remain opportunistic. With variable costs (2025/26) of almost \$2500 per ha and gross margins of only \$112 per ha (AgEcon and CottonInfo, 2025), the long-term viability of a rainfed cropping industry in these regions and across INA more generally is still uncertain.

Importantly the continued expansion of cotton in INA will depend upon its ‘social licence to operate’, which will depend upon the operation and stewardship of land and waterways by irrigated and rainfed cotton enterprises and potentially how equitably the benefits are shared (Roth 2011, Moffat and Zhang 2014).

4.3.4 Climate change implications

To 2060, climate change is unlikely to significantly impact the rate of irrigated agricultural expansion in INA. While the region's climate presents challenges, overcoming these obstacles primarily requires an improved understanding of local environmental conditions, a common feature of all greenfield agricultural ventures. Temperature extremes at sensitive phenological stages can adversely impact on crop productivity, for example if extreme temperatures occur during flowering and pollination, cotton boll development or grain filling. Early wet-season (October to December) temperatures in INA may already exceed optimal thresholds for some crops and high soil temperatures are known to already affect seedling emergence and crop establishment (Arbrecht and Bristow 1996). Further warming could reduce yields and increase water requirements assuming no change in rainfall for some crops (Ash *et al.*, 2018). However, projections are based on existing crop varieties and technologies and changes in varieties and technologies to 2060 are uncertain but likely to be large. Historically, advancements in agronomy, breeding, and farm management have more than offset climate-related yield losses. For instance, global yields of maize have increased by 196% since 1960 due to technological improvements, though stationary climate conditions would have led to a 208% increase (Ritchie, 2024). In crops such as rice and wheat, CO₂ fertilization has counterbalanced yield losses from temperature increases (Moore, 2020). While in other crops such as cotton, increases in minimum temperatures under projected future climates, is likely to decrease the frequency of early season cold shocks in inland regions of INA, lengthen reproductive periods and potentially increase yields (Broughton, Nunn and Bange, 2024). As a result, cotton may become more financially viable in some places across INA such as the upper Flinders catchment, where planting dates are constrained by minimum temperatures during key stages of boll development and the reliability of surface water during the early-to-mid wet season (Petheram *et al.*, 2015).

The most significant impact of climate change on irrigated agriculture in INA by 2060 will likely stem from long-term shifts in rainfall patterns. While future precipitation and runoff projections remain uncertain for much of INA (Petheram *et al.*, 2012; Zheng *et al.*, 2024), there is strong agreement among climate models that southeastern Australia, including the MDB, will experience a drier climate characterised by reduced annual rainfall and higher potential evaporation rates (Zheng *et al.* 2024). Hence it is plausible that under favourable external economic conditions, climate change to 2060 at least, could drive irrigated agricultural expansion in INA rather than constrain it.

4.3.5 Potential for government intervention and likely scale of developments

Although the government sponsored ORIA encompassed 33% of the irrigated area across INA in 2023, substantial government investment in new water infrastructure in INA is unlikely, except for initiatives aimed at increasing the water security of urban and high-value industries (e.g. critical minerals), upgrading existing infrastructure to improve water-use efficiency and commissioning feasibility studies (Australian Government, 2015). A key principle of Australia's National Water Initiative (NWI, 2025) is to implement user-pays policies, ensuring pricing transparency in water storage and delivery while achieving full cost recovery for water planning and management. Moreover, research indicates that Traditional Owners across INA generally prefer small-scale irrigation developments that rely on groundwater extraction or water harvesting, with large dam projects consistently being the least favoured option (Barber, 2013; Lyons and Barber, 2018). These findings suggest that, apart from the ORIA, where significant historical investments have already been made and agreements with Traditional Owners have been established (Department of the Premier and Cabinet, 2019), future irrigation developments in INA will likely be small in scale, typically 50–2,000 ha, and exhibit a patchy pattern rather than large contiguous expansions.

As a result, future government intervention in irrigation-related infrastructure across INA is expected to focus on enabling infrastructure, such as post-harvest processing facilities and improvements to export logistics, including upgrades to sea and airport capacities. Additionally, government support may be directed toward providing pre-competitive information to reduce investment barriers (Petheram *et al.*, 2018b,c,d;). The extent of such support will likely depend on the potential of emerging industries, such as carbon markets, low carbon liquid fuel production and biodiversity-related enterprises, to generate employment and contribute to regional economic development.

5. Conclusions

In 2023, irrigated and rainfed agriculture and plantation forestry occupied a small fraction of the INA study area, covering only 0.02% and 0.04%, respectively. By jurisdiction, the irrigation occurred in WA (48%), the NT (39%), and Qld (13%). Rainfed cropping and forestry were predominantly concentrated in the NT (80%), with no recorded rainfed agriculture in northern WA (Table 2).

Between 1999 and 2023, irrigated land increased from 32,904 ha to 60,303 ha, with northern WA exhibiting the highest expansion rate. Rainfed cropping and forestry grew at a significantly higher rate, expanding nearly fourfold from 28,811 ha to 134,362 ha, primarily in the NT (77%) (Table 3). The number of reporting units with irrigation or rainfed agriculture also increased, reflecting a broader distribution of agricultural activities (Supplementary Table 1). Irrigated land uses were relatively diverse (Table 4), while rainfed land uses were dominated by sorghum (53%) and plantation forestry (35 %).

Water sources and irrigation methods varied significantly by region. Surface water was the primary source in northern WA (83%) and inland Qld (58%), while groundwater dominated

in the NT (91%) (Supplementary Table 2). Surface irrigation was the most widely used system, particularly in the ORIA, while micro irrigation prevailed in the NT (Supplementary Table 3). Irrigation was strongly linked to freehold land tenure (Figure 5) due mostly to the expansion of the ORIA and access to affordable water, with significant investment in structured water management frameworks in regions like the Ord River and Flinders catchments.

Overall, the findings highlight the expansion of irrigated and rainfed agriculture in INA, driven by regional infrastructure, water availability, and economic incentives. Continued development will likely depend on sustainable water management and policy support to balance agricultural growth with environmental considerations as well as technical innovations. While broadacre cropping, aside from cotton, is unlikely to become commercially viable in the near future, irrigated cotton is poised for substantial growth, driven by the recent construction of two cotton processing plants, but is heavily dependent on the price received for cotton lint. Horticultural expansion remains market-dependent and is likely to be constrained by competition from other tropical regions. Meanwhile, widespread integration of irrigated fodder crops into beef enterprises may allow reduced dependence on live export, and therefore lower risk, but would require sustained higher beef prices to be viable.

7. References

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The authors report there are no competing interests to declare.

Data availability statement

The data that supports the findings of this study are available on the CSIRO Data Access Portal, <https://doi.org/10.25919/fgjx-w567>.

1006 **Supplementary material**

1007 Supplementary Table 1 Irrigated and rainfed cropping, horticulture and forestry in the study area, in 2023 and 1999, in
1008 Inland Northern Australia, presented by catchment by jurisdiction

Reporting unit	Unit area	Irrigated land area			Rainfed land area		
		1999	2023	Mean annual change	1999	2023	Mean annual change
Units	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)
Western Australian catchments							
ASHBURTON RIVER	7,569,900	0	1,029	0	0	0	0
CAPE LEVEQUE COAST	2,291,939	585	692	+4	0	0	0
DE GREY RIVER	5,671,640	0	0	0	0	0	0
DRYSDALE RIVER	2,597,990	0	0	0	0	0	0
FITZROY RIVER	9,381,736	7	456	+19	0	0	0
FORTESCUE RIVER	4,976,000	0	830	+35	0	0	0
GASCOYNE RIVER	7,583,513	1,050	1,069	+1	0	0	0
ISDELL RIVER	1,971,561	0	0	0	0	0	0
KEEP RIVER (WA)	578,943	0	5,443	+227	0	0	0
KING EDWARD RIVER	1,718,545	7	7	0	0	0	0
LENNARD RIVER	1,474,667	0	0	0	0	0	0
LYNDON-MINILYA RIVERS	5,268,200	325	329	+0	0	0	0
MACKAY (WA)	11,231,648	0	0	0	0	0	0
ONSLow COAST	1,754,010	0	0	0	0	0	0
ORD RIVER (WA)	4,402,897	13,578	16,335	+115	0	0	0
PENTECOST RIVER	2,913,530	0	0	0	0	0	0
PORT HEDLAND COAST	3,517,145	0	0	0	0	0	0
PRINCE REGENT RIVER	1,486,712	0	0	0	0	0	0
GREAT SANDY DESERT	30,769,532	295	2,525	+93	0	0	0
Northern Territory catchments							
ADELAIDE RIVER	746,004	3,527	4,268	+31	1,423	6,680	+219
BARKLY	12,400,013	0	0	0	0	6,071	+253
BLYTH RIVER	908,638	0	0	0	0	0	0
BUCKINGHAM RIVER	836,091	0	15	+1	0	0	0
BURT	3,882,349	0	0	0	0	0	0
CALVERT RIVER	1,003,272	0	0	0	0	0	0

Reporting unit	Unit area	Irrigated land area			Rainfed land area		
		1999	2023	Mean annual change	1999	2023	Mean annual change
DALY RIVER	5,319,716	4,807	11,870	+294	16,240	51,080*	+1452
EAST ALLIGATOR RIVER	1,536,492	0	1	+0	0	0	0
FINKE RIVER	4,388,243	30	70	+2	0	0	0
FINNISS RIVER	937,348	2,769	2,525	-10	1,700	6,120	+184
FITZMAURICE RIVER	1,017,784	0	0	0	0	0	0
GEORGINA RIVER (NT)	9,984,117	0	0	0	0	109	+5
GOOMADEER RIVER	558,175	0	0	0	0	0	0
GOYDER RIVER	1,039,057	0	0	0	0	0	0
HAY RIVER	6,277,131	0	0	0	0	0	0
KEEP RIVER (NT)	597,522	0	0	0	0	0	0
KOOLATONG RIVER	783,409	0	0	0	0	0	0
LIMMEN BIGHT RIVER	1,593,832	0	0	0	0	0	0
LIVERPOOL RIVER	894,096	0	0	0	0	0	0
MACKAY (NT)	21,595,795	0	0	0	0	66	+3
MARY RIVER	807,352	161	95	-3	0	75	+3
McARTHUR RIVER	1,960,654	0	0	0	0	0	0
MOYLE RIVER	705,274	0	8	+0	0	0	0
NICHOLSON RIVER (NT)	1,577,318	0	0	0	0	0	0
ORD RIVER (NT)	1,135,549	0	0	0	0	0	0
ROBINSON RIVER	1,109,869	0	0	0	0	0	0
ROPER RIVER	7,961,737	0	2,304	+96	0	1,138	+47
ROSIE RIVER	504,434	0	0	0	0	0	0
SETTLEMENT CREEK (NT)	549,342	0	0	0	0	0	0
SOUTH ALLIGATOR RIVER	1,186,771	0	0	0	0	0	0
TIWI ISLANDS	758,000	0	0	0	6,541	31,791**	+1052
TODD RIVER	5,963,645	0	341	+14	0	0	0
TOWNS RIVER	539,297	0	0	0	0	0	0
VICTORIA RIVER	7,812,870	0	77	+3	0	143	+6
WALKER RIVER	949,390	0	0	0	0	0	0
WARBURTON	964,640	0	0	0	0	0	0
WILDMAN RIVER	481,808	137	76	-3	0	0	0

Reporting unit	Unit area	Irrigated land area			Rainfed land area		
		1999	2023	Mean annual change	1999	2023	Mean annual change
WISO	22,931,138	729	1,994	+53	0	4,376	0
Queensland catchments							
ARCHER RIVER	1,384,779	0	0	0	25	0	0
COLEMAN RIVER	1,290,482	0	0	0	0	0	0
COOPER CREEK	7,377,429	419	192	-9	4	77	+3
DIAMANTINA RIVER	4,972,281	314	314	0	0	0	0
DUCIE RIVER	681,419	0	0	0	0	0	0
EMBLEY RIVER	469,191	12	20	+0	0	0	0
FLINDERS RIVER	10,971,701	403	3,497	+129	32	17,798	+740
GEORGINA RIVER (QLD)	9,518,894	0	0	0	0	0	0
GILBERT RIVER	4,628,244	419	511	+4	621	2,307	+70
HOLROYD RIVER	1,021,762	0	0	0	0	0	0
JARDINE RIVER	328,254	1	35	+1	0	0	0
LEICHHARDT RIVER	3,329,895	1,012	1,623	+25	0	4,075	+170
MITCHELL RIVER	7,152,913	1,816	1,698	-5	2,225	2,266	+2
MORNING INLET	361,154	0	0	0	0	0	0
NICHOLSON RIVER (QLD)	3,585,932	501	54	-19	0	193	0
NORMAN RIVER	5,002,764	0	0	0	0	0	0
SETTLEMENT CREEK (QLD)	1,181,575	0	0	0	0	0	0
STAATEN RIVER	2,583,846	0	0	0	0	0	0
WENLOCK RIVER	745,997	0	0	0	0	0	0
WATSON RIVER	467,673	0	0	0	0	0	0

Table footnotes *14,864 ha of this area is planted with African mahogany (*Khaya senegalensis*) as timber plantations in the Douglas – Daly area; **All this area is planted with black wattle (*Acacia mangium*) as timber plantations on Melville Island.

Type of water	Groundwater		Surface water					Unknown	Total
Source of water supply	Private bores	Irrigation scheme bores	Gully dam	Direct river take	Off - stream storage	Large dam scheme	Waste water reuse		
Units	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)
Inland Northern Australia	26,269	1,398	441	1,104	3,926	21,773	1,989	3,403	60,303
Inland Northern Australia split between jurisdictions									
Western Australia	3,207	1,398	0	202	0	21,773	1,788	350	28,718
Northern Territory	21,491	0	122	673	0	0	60	1,295	23,641
Inland Queensland	1,571	0	319	229	3,926	0	141	1,758	7,944
Key regions in Inland Northern Australia									
Carnarvon Irrigation District	0	1,365	0	0	0	0	0	0	1,365
Pilbara Hinterland Ag Dev Initiative	102	0	0	0	0	0	1,757	0	1,859
Skuthorpe (Broome)	244	0	0	0	0	0	0	3	247
Ord River Irrigation Area	0	0	0	0	0	19,651	0	0	19,651
Western Davenport - Central Plain	863	0	0	0	0	0	0	0	863
Mataranka Region	2,239	0	0	0	0	0	0	0	2,239
Katherine Region	5,529	0	0	250	0	0	33	793	6,604
Douglas-Daly Area	3,819	0	0	0	0	0	0	51	3,870
Darwin Rural Area	6,491	0	52	257	0	0	27	138	6,964
Armraynald Plain	0	0	224	220	1,170	0	0	0	1,614
Upper Flinders	647	0	0	0	668	0	0	46	1,361
Gilbert River Agricultural Precinct	473	0	0	0	0	0	0	0	473
Julatten	0	0	0	0	0	0	63	1,433	1,496

Supplementary Table 3 Irrigation system used on irrigated lands in 2023 presented by jurisdiction and key region as well as the whole of INA

Type of irrigation system	Micro systems	Overhead systems		Surface systems		Unknown	Total
Application method		Centre pivot	Other*	Furrow	Flood		
Units	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)
Inland Northern Australia	22,667	8,308	1,424	19,218	4,887	3,799	60,303
Inland Northern Australia split between jurisdictions							
Western Australia	4,929	4,637	366	17,983	201	602	28,718
Northern Territory	17,288	3,297	719	533	320	1,484	23,641
Inland Queensland	450	374	339	702	4,366	1,714	7,944
Key regions in Inland Northern Australia							
Carnarvon Irrigation District	1,365	0	0	0	0	0	1,365
Pilbara Hinterland Ag Dev Initiative	0	1,859	0	0	0	0	1,859
Skuthorpe (Broome)	68	88	88	0	0	3	247
Ord River Irrigation Area	1,180	34	0	17,886	201	350	19,651
Western Davenport - Central Plain	0	863	0	0	0	0	863
Mataranka Region	2,239	0	0	0	0	0	2,239
Katherine Region	5,254	384	79	94	0	793	6,604
Douglas-Daly Area	3,119	649	0	0	0	102	3,870
Darwin Rural Area	6,150	40	179	0	320	277	6,964
Armraynald Plain	0	0	0	358	1,256	0	1,614
Upper Flinders	175	263	0	218	685	20	1,361
Gilbert River Agricultural Precinct	238	0	164	71	0	0	473
Julatten	37	74	8	0	63	1,314	1,496

Table footnote: *includes lateral, sprinkler and winch methods

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1021 Supplementary Table 4 Rainfed land uses in Inland Northern Australia in 2023, presented by key region

Rainfed land use	Commodity	Western Australia							Northern Territory					Queensland							
		Carnarvon	Irrigation	Pilbara	Hinterland	Skuthorpe	Ord River	Irrigation	Western	Davenport - Mataranka	Katherine	Region Douglas-Daly	Area Darwin Rural	Area	Armagh	plain	Upper	Flinders	Gilbert River	As Proiect	Julatten
		(ha)			(ha)	(ha)	(ha)		(ha)	(ha)	(ha)	(ha)	(ha)		(ha)		(ha)	(ha)	(ha)		(ha)
Plantation forests	African mahogany	0			0	0	0		0	0	0	8,665	0		0		0	0	0		0
	Undefined	0			0	0	0		0	0	416	0	854		0		0	28	73		
Hay & silage	Forage sorghum	0			0	0	0		0	0	9,933	4,888	11,924		0		6,125		0		0
	Rhodes grass	0			0	0	0		0	0	0	0	0		272		72		0		0
Cereals	Sorghum	0			0	0	0		0	0	0	0	45		3,996		1,349		0		0
Cotton		0			0	0	0		0	0	0	1,875	0		0		0		0		0
Cropping	Undefined	0			0	0	0		0	0	5	0	0		0		5		513		0
Perennial horticulture		0			0	0	0		0	0	2	0	51		0		0		127		0
Total		0			0	0	0		0	0	10,356	15,428	12,874		4,268		7,551		668		73
											6	8	4								

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