Using Luenberger Environmental Indicator to Measure Environmental Efficiency of Agricultural Water Use

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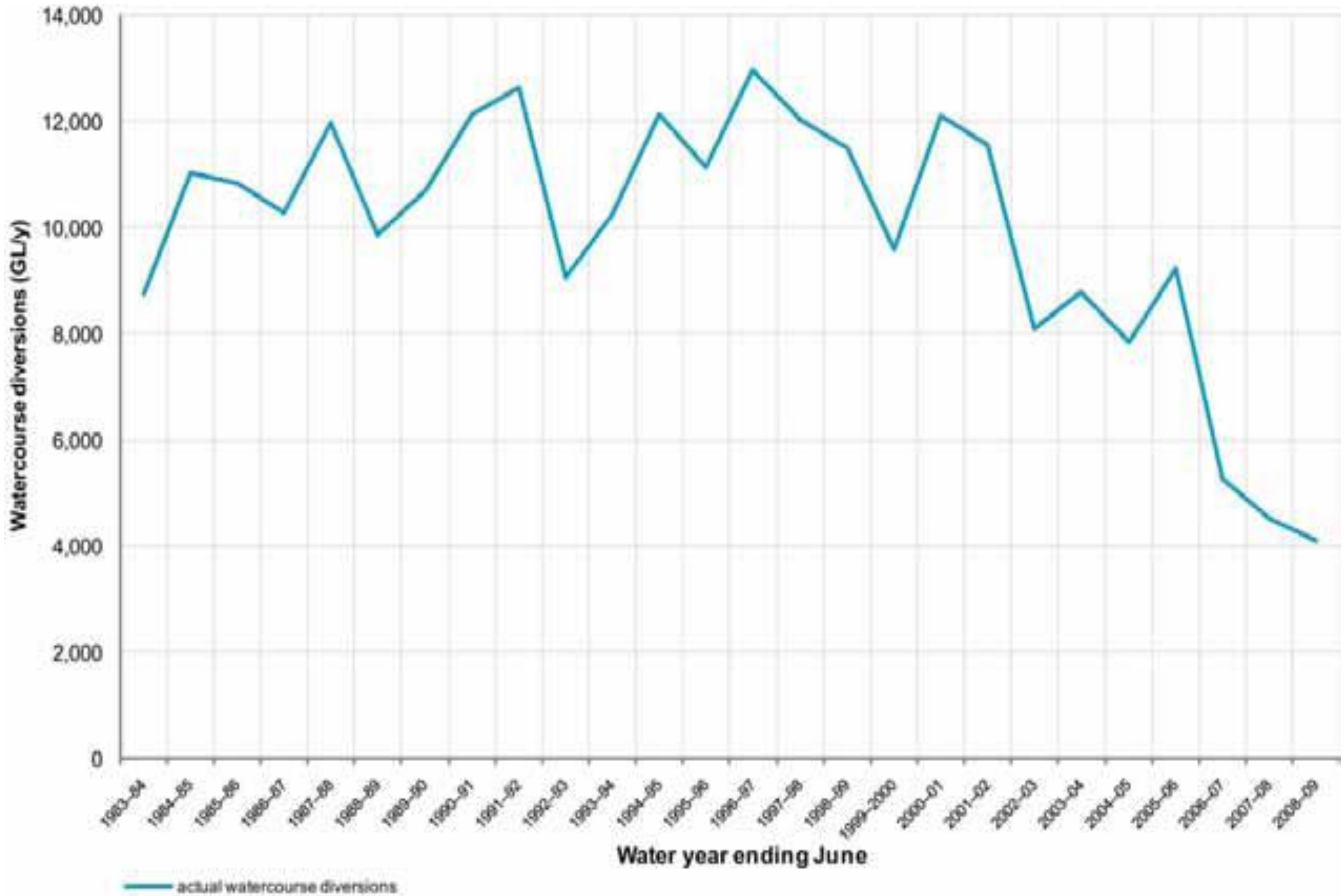
Motivation

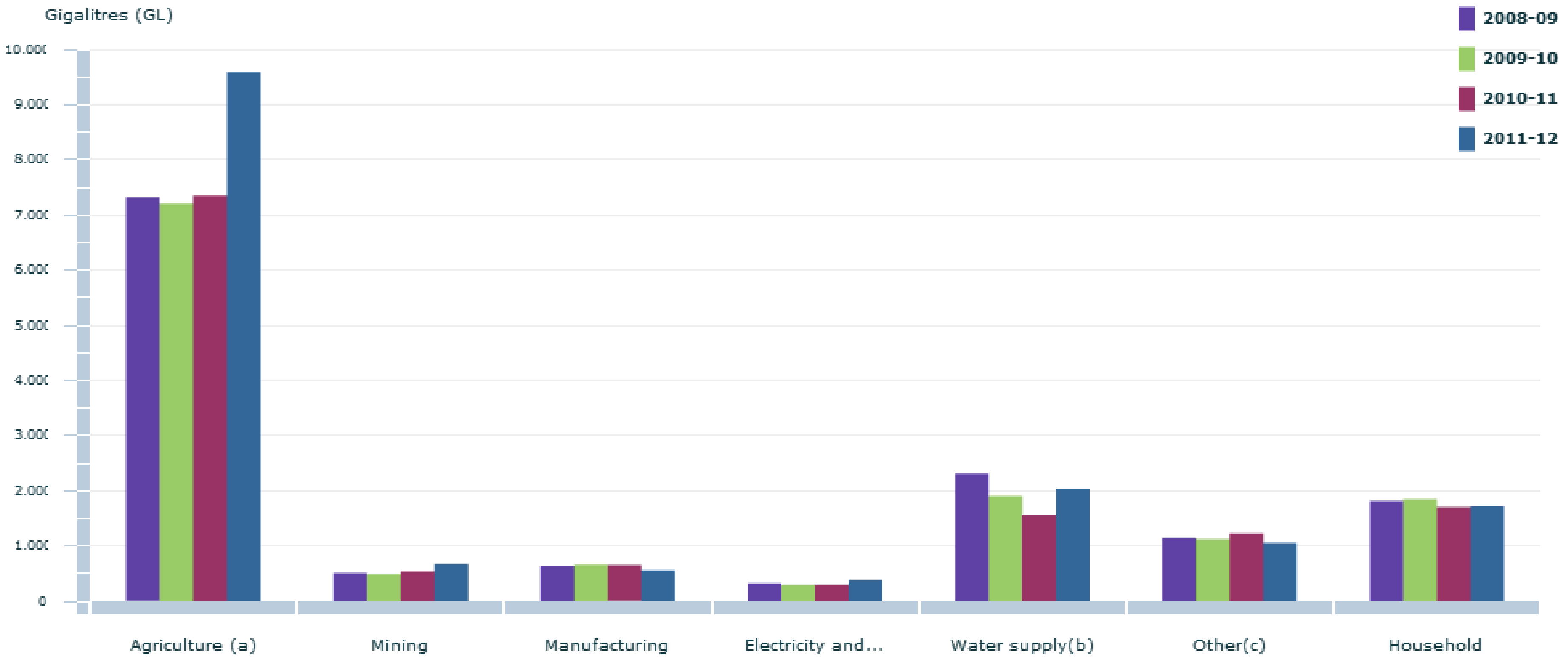
- Water – a scarce resource.
- Key for the irrigation industry.
- But, irrigated agriculture creates substantial environmental pressures by withdrawing large quantities of water.
- Excessive water withdrawal leaves rivers and wetlands empty and unable to support the valuable ecosystems that depend on the water resource (Azad and Ancev, 2010; Grafton et al., 2010; Quiggin, 2001).
- A key challenge is to balance water extractions for agricultural production and other uses with provision of appropriate environmental flow to maintain healthy rivers and wetlands.

Surface water use in the MDB, Australia



Source: ABS (2010)

Agricultural Water Use in Australia



Source: ABS (2014)

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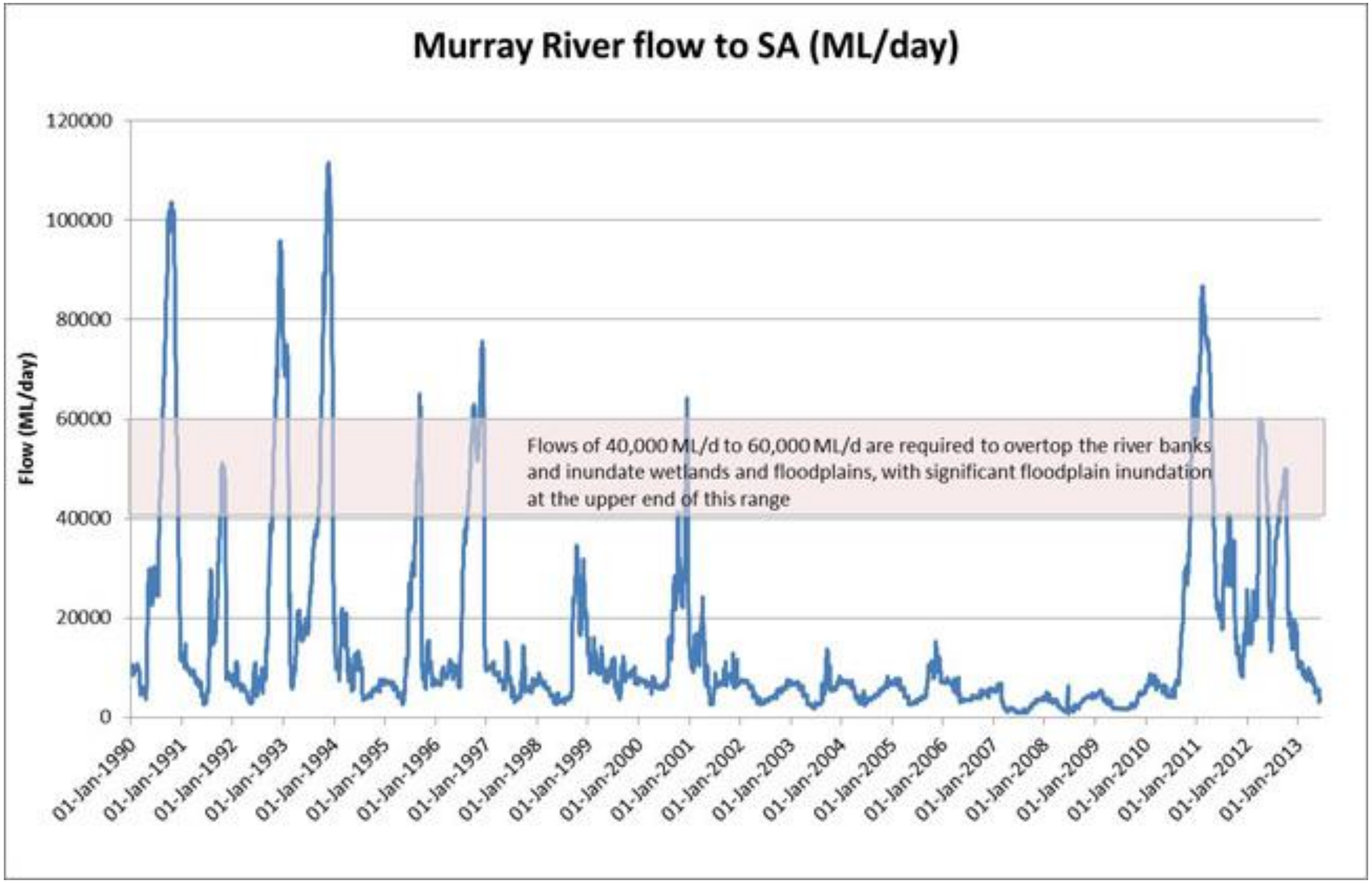
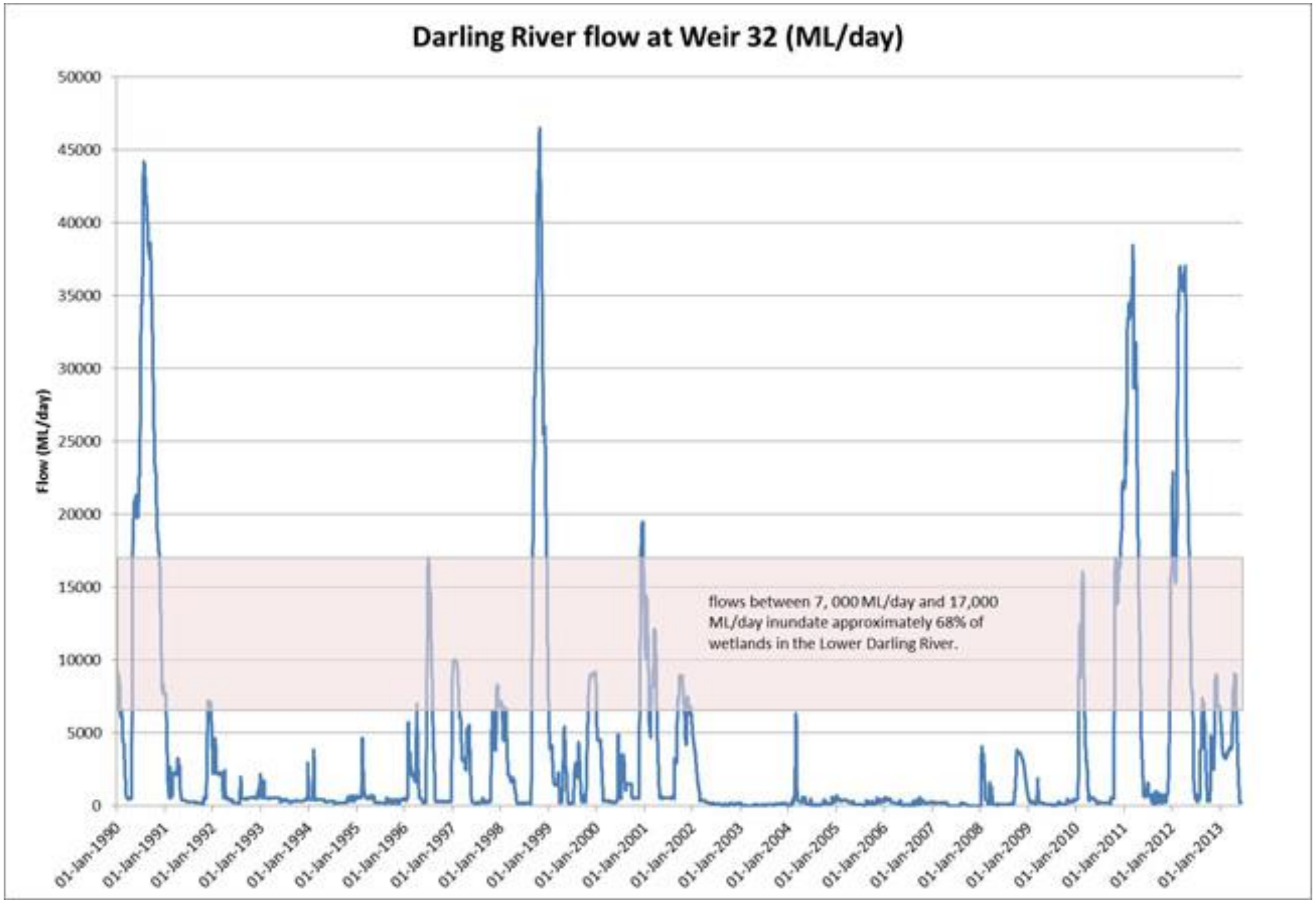
Flow Rates of the Murray River, 1990-2013



Source: Murray Darling Basin Authority

Flow Rates of the Darling River, 1990-2013



Source: Murray Darling Basin Authority

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How to think about tradeoffs?

Enterprise A

Enterprise B

Enterprise C

Enterprise D

Motivation

- Environmental effects have been incorporated in the efficiency modelling framework in the last 25-30 years (Färe and Grosskopf, 2004 ,Tyteca, 1996).
- Most of the efficiency models are based on a ratio-based approach (i.e., Malmquist index, Malmquist-Luenberger index, and recently developed Environmental Performance Index).
- Ratio-based indices do not directly reflect the real magnitude of the environmental effects (Azad and Ancev, 2013).
- Lack of adequate research in this area to develop appropriate methods and tools to measure relative environmental efficiency across space.

Objectives of the Study

- To propose a new way of using the Luenberger productivity indicator to measure environmentally adjusted efficiency.

- To illustrate the use of the new indicator by measuring relative performance of irrigated enterprises across space.

The Luenberger Productivity Indicator

› The Luenberger indicator is a difference-based productivity approach.

› More general than the ratio-based Malmquist index: can address simultaneously input contraction and output expansion.

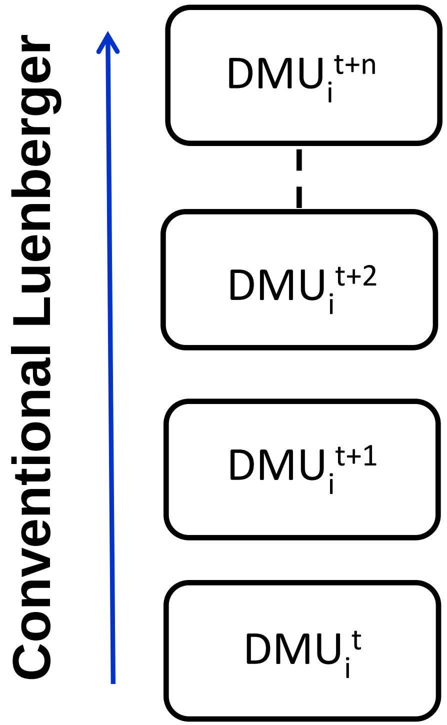
› Compatible with multiple inputs and output production system.

› Does not imply restricted profit maximisation, or restricted cost minimisation as do the Malmquist based indices (Williams et al., 2011).

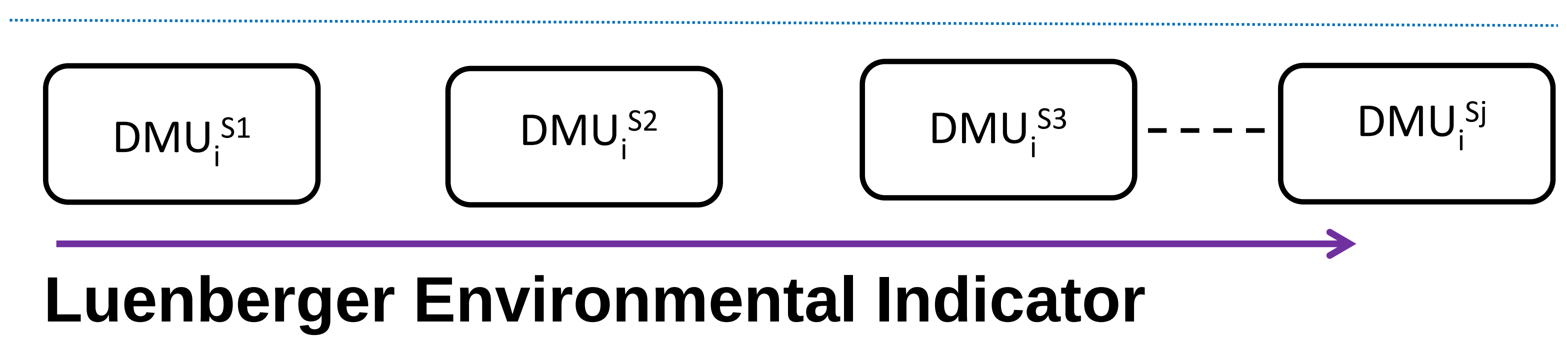
Modification of the Standard Luenberger Productivity

- The Luenberger indicator has been applied in productivity and efficiency measurement in time-varying contexts (i.e. with time series data).
- Dynamic productivity measurement approach, which can generally be employed to measure productivity growth of decision making units (DMUs) across time.
- Introducing a new approach based on the Luenberger indicator to measure efficiency of DMUs across space.

New Direction of the Luenberger Productivity Indicator



Temporally oriented Luenberger index does not allow direct comparison of performance among DMUs that operate in spatially distinct areas.



Conceptual Framework: Luenberger Environmental Indicator

› Consider a multi-output production technology:

vector of inputs: $x = (x_{1,}\, \dots, x_N) \in \Re_+^N$

desirable outputs: $d = (d_1, \dots, d_M) \in \Re_+^M$

undesirable outputs: $u = (u_1, \dots, u_J) \in \Re_+^J$

The production technology:

$$P(x) = \{(d, u): x \text{ can produce } (d, u)\}.$$

Two assumptions:

Weak disposability of outputs

Null-jointness

Directional Distance Function: Component of Luenberger Environmental Indicator

- Define a directional vector: $\mathrm{g} = (\mathrm{g}_{d,}\, \mathrm{g}_{u})$
- Directional distance function:

$$\vec{D}_o(x, d, u;\ \mathrm{g}_{d,} - \mathrm{g}_{u,}) = \sup\{\beta : (d + \beta \mathrm{g}_{d}\,, u - \beta \mathrm{g}_u) \in P(x)\}.$$

This function seeks the maximum feasible expansion of desirable output in the g_d direction and the largest possible contraction of undesirable outputs in the g_u direction.

When comparing efficiency of a production unit between regions (i.e., ***a*** and ***b*)**, the directional distance function for a given region ***a*** can be written as:

$$\vec{D}_o^a(x^a, d^a, u^a;\ \mathrm{g}_{d,} - \mathrm{g}_u) = \sup\{\beta : (d^a + \beta \mathrm{g}_d\,,\ u^a - \beta \mathrm{g}_u) \in P^a(x^a)\}.$$

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Luenberger Environmental Indicator

$$LEI_a^b = \frac{1}{2}[\vec{D}_o^b(x^a, d^a, u^a; \mathrm{g}_{d,} {-}\mathrm{g}_u) - \vec{D}_o^b(x^b, d^b, u^b; \mathrm{g}_{d,} {-}\mathrm{g}_u) + \vec{D}_o^a(x^a, d^a, u^a; \mathrm{g}_{d,} {-}\mathrm{g}_u) - \vec{D}_o^a(x^b, d^b, u^b; \mathrm{g}_{d,} {-}\mathrm{g}_u)]$$

If the value of LEI_a^b is greater than zero, it implies that the efficiency of a given DMU is greater in region b than in region a.

Decomposition: Luenberger Environmental Indicator

Luenberger environmental indicator can be decomposed into two components: (Following Chambers et al., 1996)

efficiency variation

$$LEI_a^b = [\vec{D}_o^a(x^a, d^a, u^a; g_{d,} - g_u) - \vec{D}_o^b(x^b, d^b, u^b; g_{d,} - g_u)] + \frac{1}{2}[\vec{D}_o^b(x^b, d^b, u^b; g_{d,} - g_u) - \vec{D}_o^a(x^b, d^b, u^b; g_{d,} - g_u) + \vec{D}_o^b(x^a, d^a, u^a; g_{d,} - g_u) - \vec{D}_o^a(x^a, d^a, u^a; g_{d,} - g_u)]$$

technological variation

Graphically

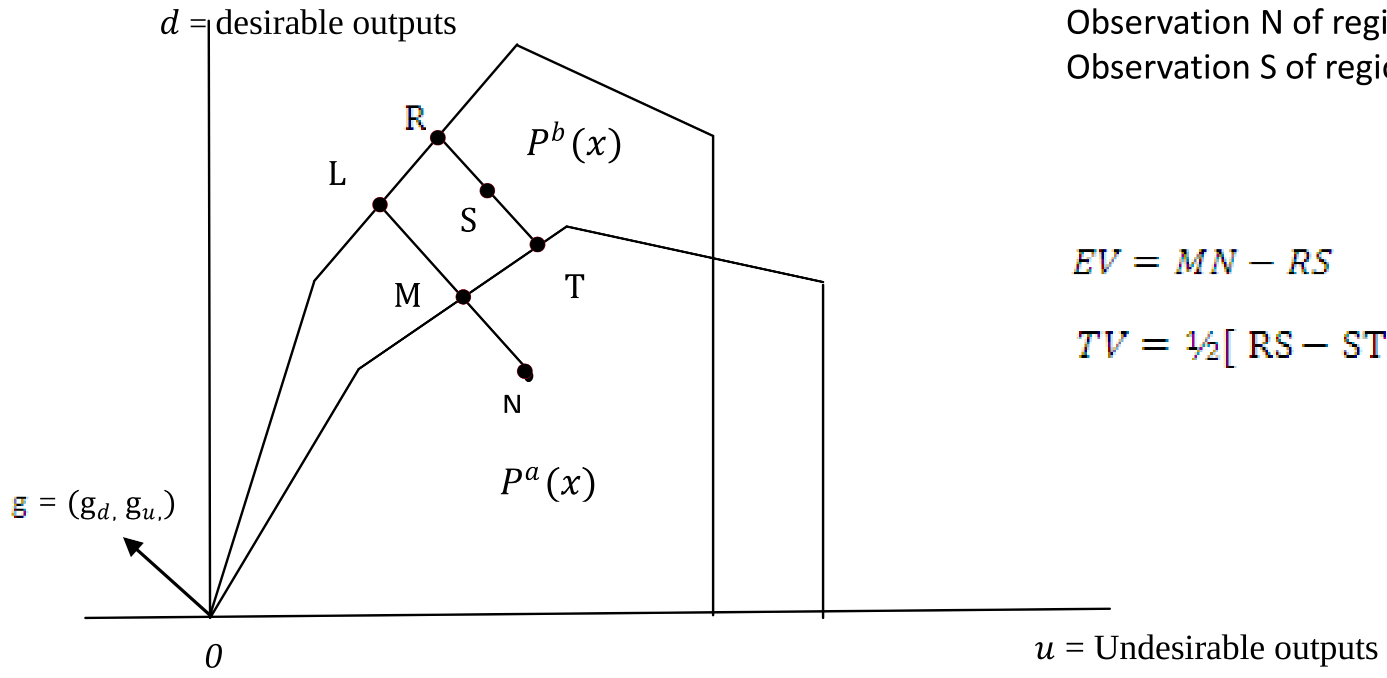


Figure : The Luenberger environmental indicator

<u>Comparison:</u>
Observation N of region a
Observation S of region b

$$EV = MN - RS$$

$$TV = ½[\, RS - ST + LN - MN]$$

Data and Variables

- Australian irrigated agriculture – 10 **types of irrigated enterprises**
- **17 NRM regions** within Murray-Darling Basin;
- We use NRM level data – **total sample size : 130**

- **Inputs:** Volume of applied irrigation water
  All production cost excluding irrigation cost
- **Desirable outputs**: Gross revenue
- **Undesirable outputs:** Ecologically weighted water withdrawal index, and Salinity impact from irrigation activity (Azad and Ancev, 2010)

Water Withdrawal Index

- **Water withdrawal index**: Amount of water withdrawn for an enterprise per year as a proportion of total annual water available in a NRM region.

$$WWI_{ij} = \frac{A_{ij} \times R_{ij}}{W_j}$$

WWI_{ij} = water withdrawal index of an enterprise i $(i = 1,...,10)$

in j $(j = 1,...17)$ NRM region

A_{ij} = area under irrigation for enterprise i within j region

R_{ij} = water application rate for enterprise i in region j

W_j = average annual surface water availability in j region

Ecological Assets Index

Ecological assets index: constructed based on the existence and importance of ecological assets within a NRM region.

$$EAI_j = \sum_{r=1}^{R} \left(\frac{C_{rj}}{N_c} \times A_{rj}\right) + d_{jk} \sum_{k=1}^{K} \sum_{r=1}^{R} \left(\frac{C_{rk}}{N_c} \times A_{rk}\right)$$

EAI_j = ecological assets index of j^{th} NRM region

C_{rj} = no. of Ramsar criteria *r* meet by RW in region j

C_{rk} = no. of Ramsar criteria *r* meet by RW in the downstream regions k affected by water withdrawals in region j

A_{rj} = Area of *r*th Ramsar wetland region j

A_{rk} = Area of Ramsar wetland in downstream regions k

N_C = maximum number of Ramsar criteria

d_{jk} = proportion of negative impact on EAs in DR k attributed to WW in j

Estimation of Luenberger Environmental Indicator

We assume that there are $k = 1, \ldots, K$ observations and two regions a and b.

In order to estimate the first component of the Luenberger environmental indicator, $\vec{D}_o^b(x^a, d^a, u^a; g_{d,} {-g_u})$, the following linear programming model can be formulated:

$$\vec{D}_o^b(x^{k',a}, d^{k',a}, u^{k',a}; g_{d,} {-g_u}) = \max \beta$$

$$\text{s.t.} \sum_{k=1}^{K} z_k^b\, d_{km}^b \geq d_{k'm}^a + \beta g_{dm}\,, \quad m = 1, \ldots, M$$

$$\sum_{k=1}^{K} z_k^b\, u_{kj}^b = u_{k'j}^a - \beta g_{uj}\,, \quad j = 1, \ldots, J$$

$$\sum_{k=1}^{K} z_k^b\, x_{kn}^b \leq x_{k'n}^a\,, \quad n = 1, \ldots, N$$

$$z_k^b \geq 0\,, \quad k = 1, \ldots, K\,.$$

Case Study: Irrigated Agriculture Industry, Murray-Darling Basin

Table 1. Mean values of the economic and environmental variables of the production model

Irrigated enterprises	Volume of water applied (GL)	All cost (excluding water) (Million AUD)	Gross revenue (Million AUD)	Ecologically weighted water withdrawal index ('000')	Salinity impact (tonnes/annum)
Cotton	103.91	33.46	56.66	99.686	283.16
Rice	60.27	5.97	20.11	60.574	78.90
Cereal crops for grain/seed	38.41	7.91	17.73	43.678	289.03
Cereal crops cut for hay	8.40	1.96	3.52	13.680	75.35
Pasture for grazing	64.46	10.21	23.18	160.976	645.85
Pasture for hay and silage	28.98	7.22	14.87	56.856	266.69
Other broadacre crops	4.82	1.48	3.12	6.196	50.68
Vegetables	10.28	36.36	44.56	23.684	50.45
Fruit and nut trees	32.03	124.28	184.18	51.739	164.58
Grapevines	44.39	86.31	132.15	58.653	189.21

Estimated Value: Luenberger Environmental Indicator

Table 2a. Values of the Luenberger environmental indicators for irrigated enterprises

NRM Regions	Cotton			Rice			Cereal crops for grain/seed		
	LEI	*EV*	*TV*	*LEI*	*EV*	*TV*	*LEI*	*EV*	*TV*
Border River-Gwydir	0.456	0.000	0.456	-	-	-	0.594	0.000	0.594
Central West	0.340	0.425	-0.084	-	-	-	1.343	0.098	1.245
Lachlan	1.985	0.363	1.622	-	-	-	0.487	0.120	0.367
Lower Murray Darling	-	-	-	-	-	-	1.228	0.079	1.149
Murray	-	-	-	0.505	0.261	0.244	0.484	0.047	0.437
Murrumbidgee	0.601	0.155	0.446	0.675	0.261	0.414	0.384	0.044	0.340
Namoi	0.800	0.425	0.376	-	-	-	0.533	0.075	0.458
Western	0.728	0.425	0.304	-	-	-	2.289	0.704	1.586
Goulburn Broken	-	-	-	1.168	-0.164	1.332	0.280	0.005	0.275
Mallee	-	-	-	-	-	-	0.969	0.704	0.265
North Central	-	-	-	1.103	0.261	0.842	0.089	-0.034	0.124
North East (VIC)	-	-	-	-	-	-	-	-	-
Wimmera	-	-	-	-	-	-	0.083	-0.017	0.100
Border River (QLD)	0.712	0.425	0.288	-	-	-	0.369	0.067	0.302
Condamine	0.783	0.425	0.359	-	-	-	1.130	0.240	0.890
Maranao Balonne	0.815	0.425	0.390	-	-	-	1.206	0.092	1.114
SA Murray Darling Basin	-	-	-	-	-	-	-	-	-

LEI = Luenberger environmental indicator, *EV* = Efficiency variation, *TV* = Technological variation.

Estimated Value: Luenberger Environmental Indicator

Table 2b. Values of the Luenberger environmental indicators for irrigated enterprises

NRM Regions	Cereal crops cut for hay			Pasture for grazing			Pasture for hay and silage		
	LEI	*EV*	*TV*	*LEI*	*EV*	*TV*	*LEI*	*EV*	*TV*
Border River-Gwydir	0.619	0.184	0.435	0.646	0.000	0.646	0.858	0.218	0.639
Central West	3.425	-0.067	3.492	0.152	-0.696	0.848	0.573	0.147	0.427
Lachlan	0.327	-0.076	0.403	0.043	-0.680	0.723	3.279	0.679	2.601
Lower Murray Darling	-	-	-	0.897	-0.645	1.542	0.767	0.330	0.436
Murray	0.315	-0.109	0.424	0.423	0.000	0.423	0.469	0.054	0.416
Murrumbidgee	0.448	-0.046	0.494	0.039	-0.799	0.837	0.465	0.058	0.407
Namoi	1.091	-0.133	1.224	0.761	-0.768	1.529	0.603	0.063	0.540
Western	-	-	-	0.169	-0426	0.595	-	-	-
Goulburn Broken	0.236	-0.103	0.339	0.151	0.000	0.151	0.278	0.000	0.279
Mallee	0.650	0.000	0.650	0.080	-0.715	0.795	1.079	0.679	0.401
North Central	0.051	-0.100	0.151	0.173	0.000	0.173	0.111	-0.031	0.142
North East (VIC)	0.390	-0.013	0.403	0.374	0.000	0.374	0.352	-0.102	0.454
Wimmera	-	-	-	0.210	0.000	0.210	0.026	0.051	-0.026
Border River (QLD)	2.659	-0.032	2.691	2.042	-0.705	2.748	1.904	0.018	1.886
Condamine	1.618	-0.023	1.642	1.129	-0.681	1.811	1.192	0.045	1.148
Maranao Balonne	1.149	-0.063	1.212	0.951	-0.708	1.659	1.228	0.006	1.222
SA Murray Darling Basin	0.690	0.000	0.690	0.100	-0.734	0.834	0.613	0.277	0.335

LEI = Luenberger environmental indicator, *EV* = Efficiency variation, *TV* = Technological variation.

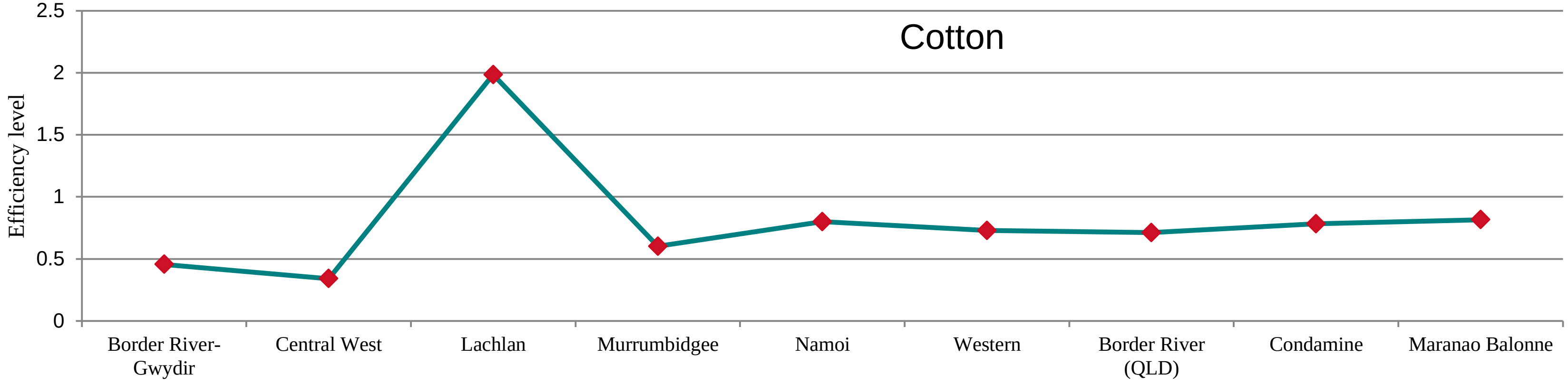
Estimated Value: Luenberger Environmental Indicator

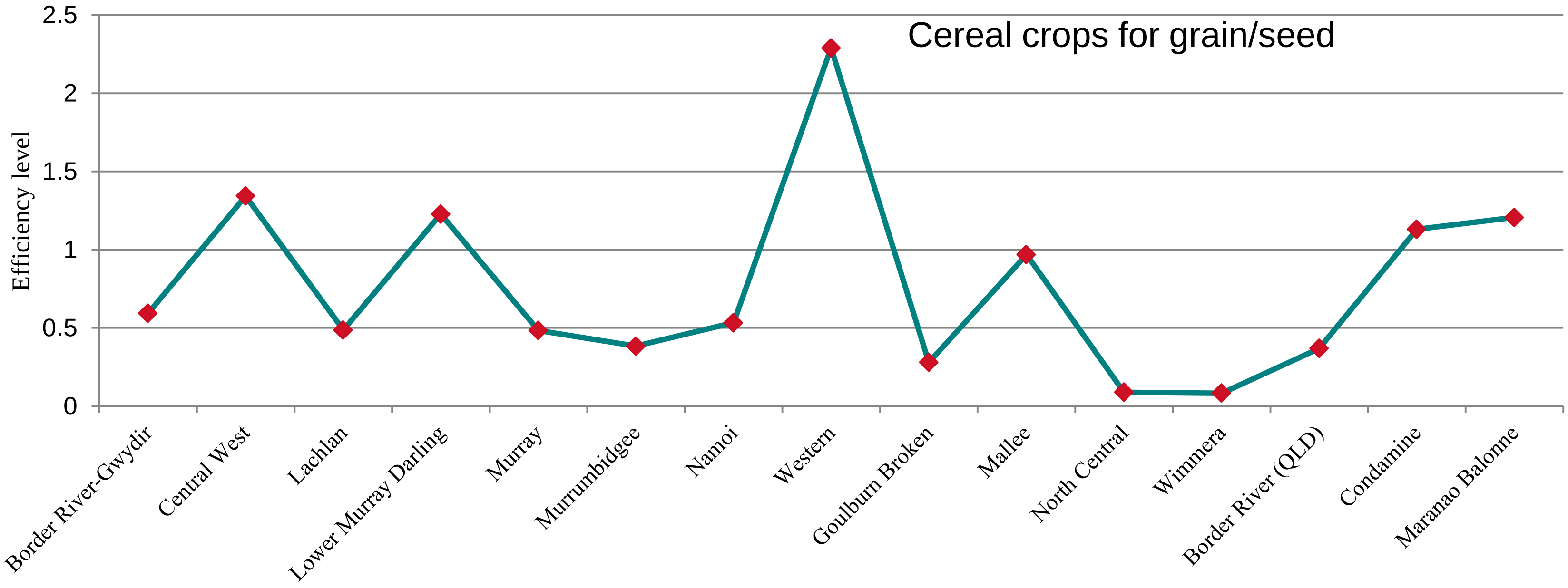
Table 2c. Values of the Luenberger environmental indicators for irrigated enterprises

NRM Regions	Other broadacre crops			Vegetables			Fruit and nut tress			Grapevines		
	LEI	*EV*	*TV*	*LEI*	*EV*	*TV*	*LEI*	*EV*	*TV*	*LEI*	*EV*	*TV*
Border River-Gwydir	0.454	-0.088	0.542	-	-	-	-	-	-	-	-	-
Central West	1.514	-0.716	2.230	0.210	-0.132	0.342	0.191	0.008	0.183	0.786	0.000	0.786
Lachlan	0.403	0.000	0.403	2.697	-0.156	2.853	1.459	0.008	1.451	2.640	0.000	2.640
Lower Murray Darling	1.360	0.000	1.360	1.033	0.000	1.033	0.524	0.008	0.516	0.436	0.000	0.436
Murray	0.064	-0.814	0.879	0.604	-0.262	0.867	0.839	0.008	0.831	0.625	0.000	0.625
Murrumbidgee	0.671	-0.488	1.159	0.575	0.000	0.575	0.716	0.008	0.708	0.519	0.000	0.519
Namoi	0.787	-0.706	1.493	-	-	-	0.723	0.008	0.715	0.654	0.000	0.654
Western	-	-	-	-	-	-	0.806	0.008	0.798	0.713	0.000	0.713
Goulburn Broken	0.330	0.000	0.330	2.181	-0.213	2.394	0.817	-0.026	0.843	1.310	0.000	1.310
Mallee	-	-	-	0.491	0.000	0.491	0.613	0.008	0.605	0.485	0.000	0.485
North Central	0.296	-0.716	1.012	0.118	-0.170	0.287	0.105	-0.049	0.154	0.894	0.000	0.894
North East (VIC)	0.088	-0.688	0.776	1.260	0.000	1.260	-	-	-	2.350	0.000	2.350
Wimmera	-	-	-	-	-	-	0.599	0.008	0.591	0.675	0.000	0.675
Border River (QLD)	1.889	0.000	1.889	0.226	-0.197	0.423	0.705	0.008	0.696	0.710	0.000	0.710
Condamine	0.813	-0.627	1.440	0.777	-0.186	0.963	0.786	0.008	0.778	0.789	0.000	0.789
Maranao Balonne	1.199	0.000	1.199	-	-	-	-	-	-	0.596	0.000	0.596
SA Murray Darling Basin	-	-	-	0.749	0.000	0.749	0.669	0.001	0.668	0.672	0.000	0.672

LEI = Luenberger environmental indicator, *EV* = Efficiency variation, *TV* = Technological variation.

Efficiency variation across regions





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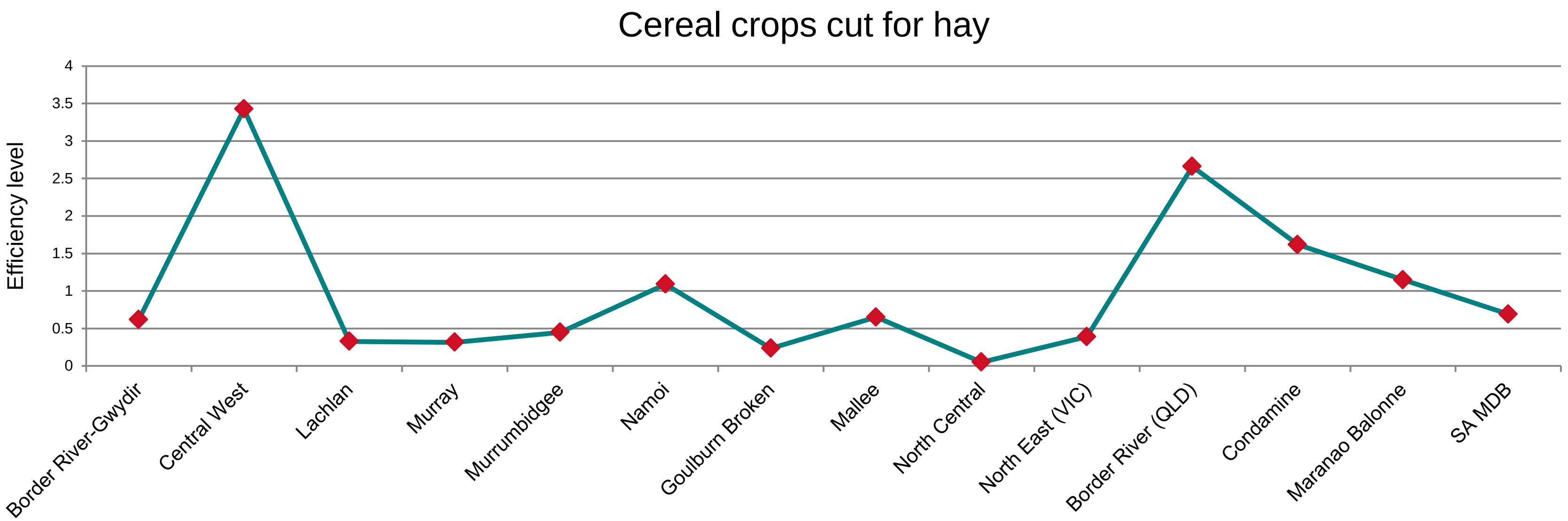

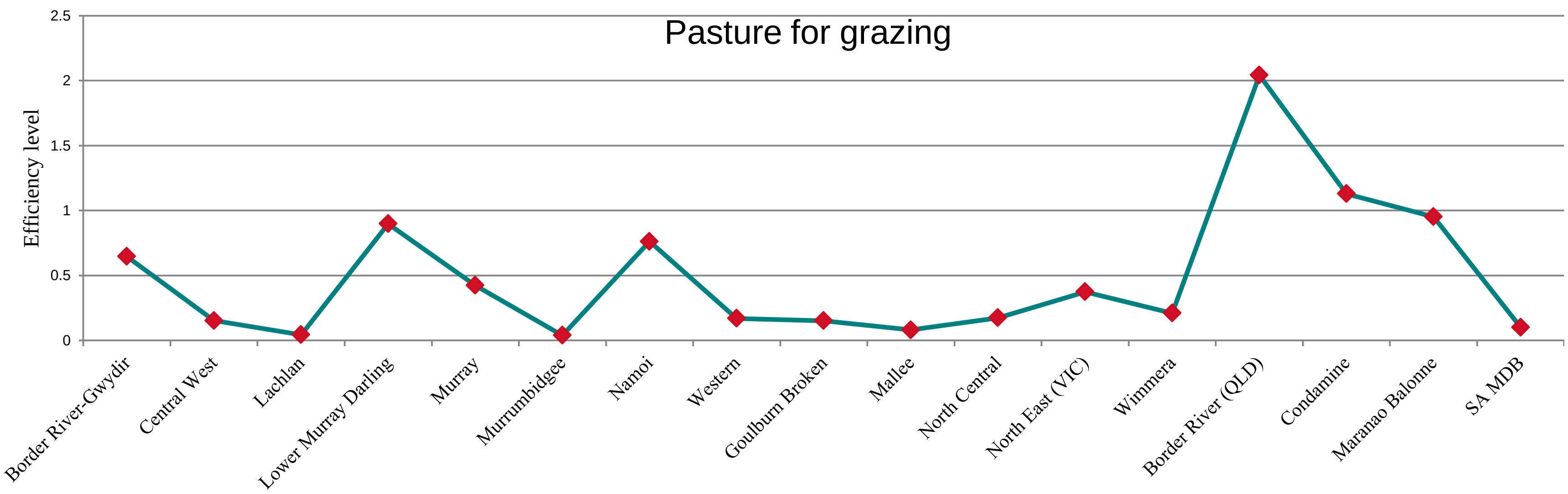

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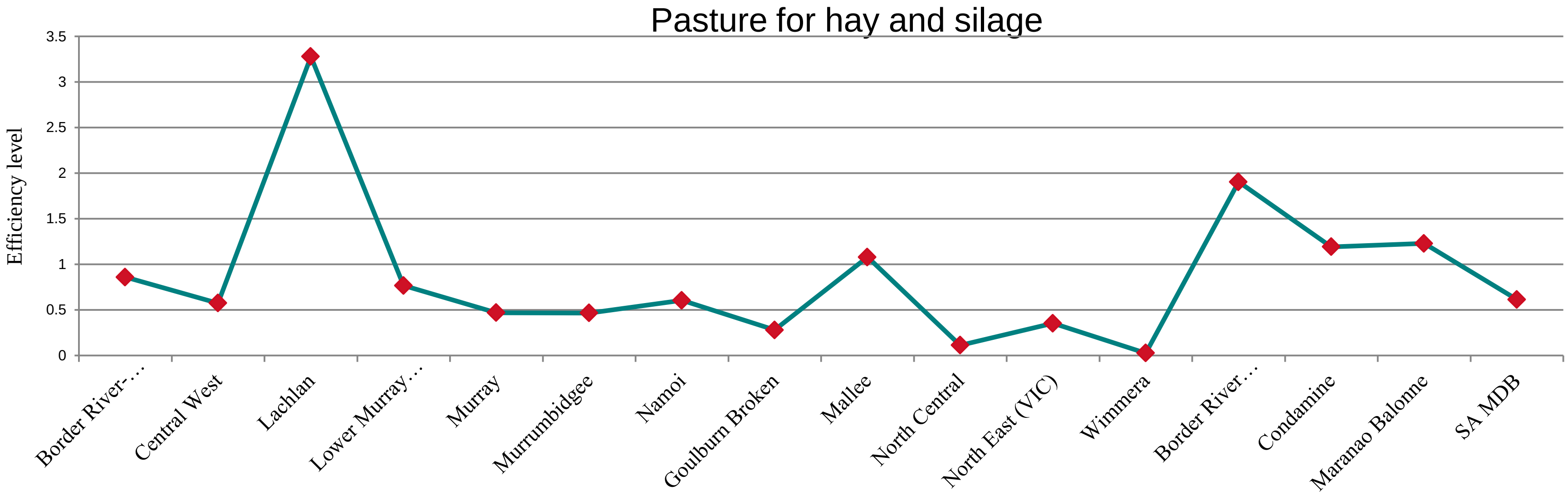

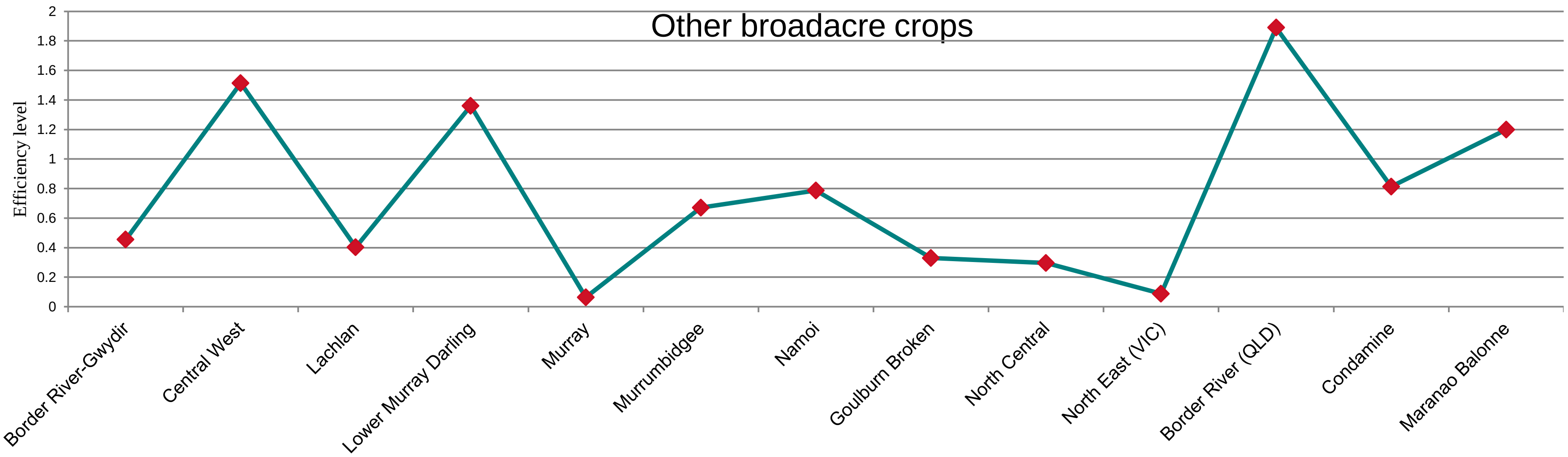

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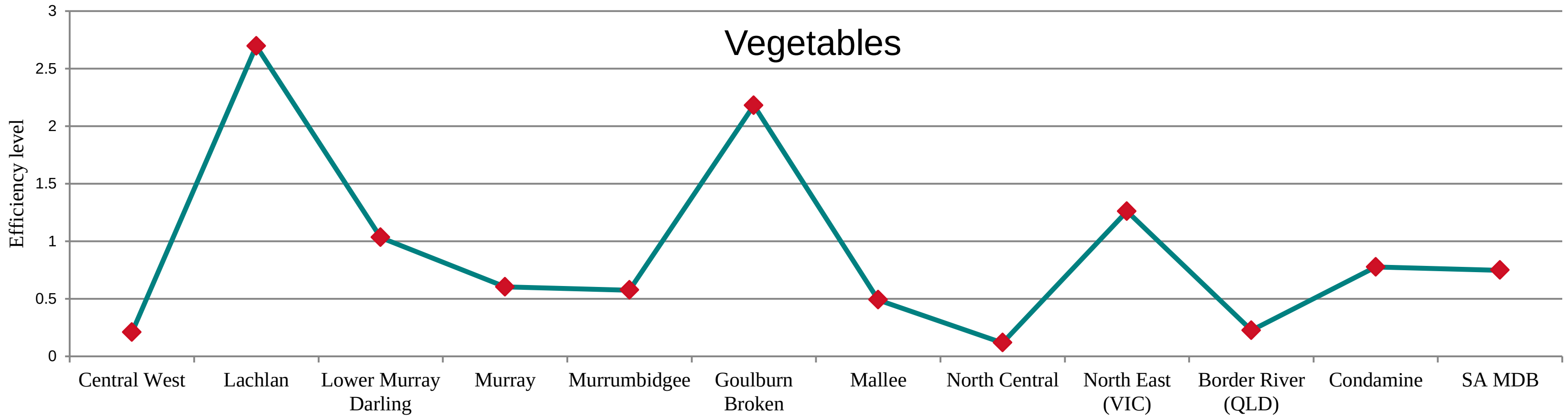

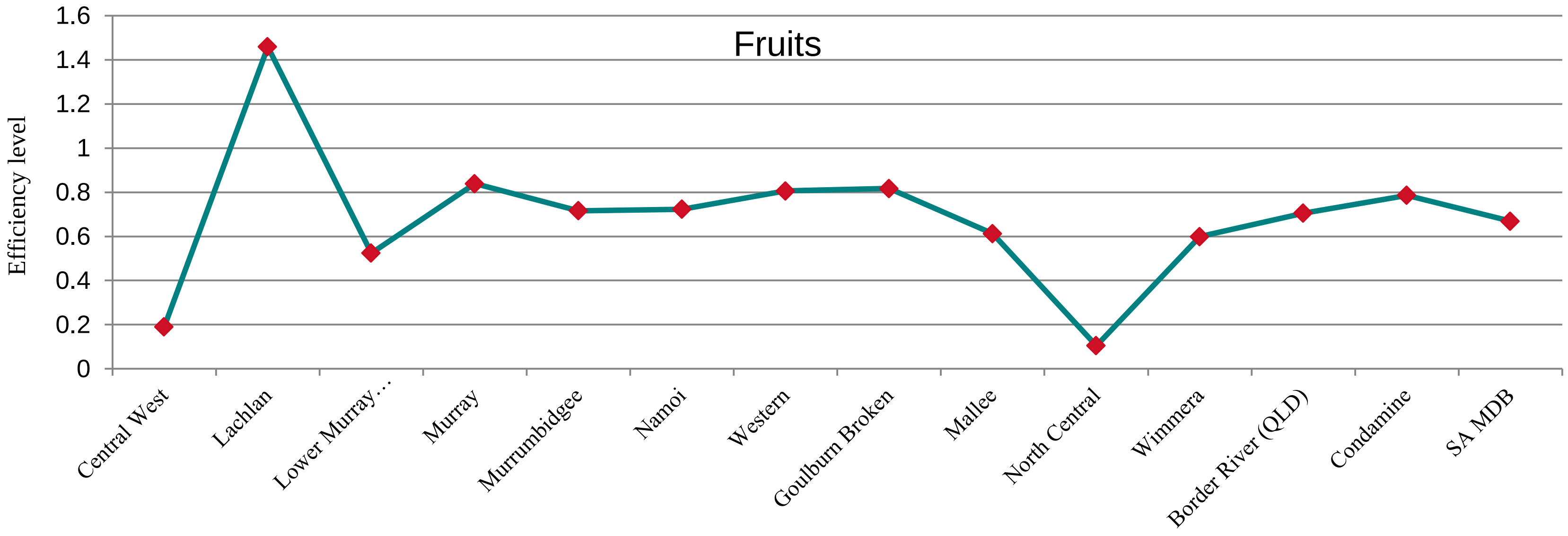

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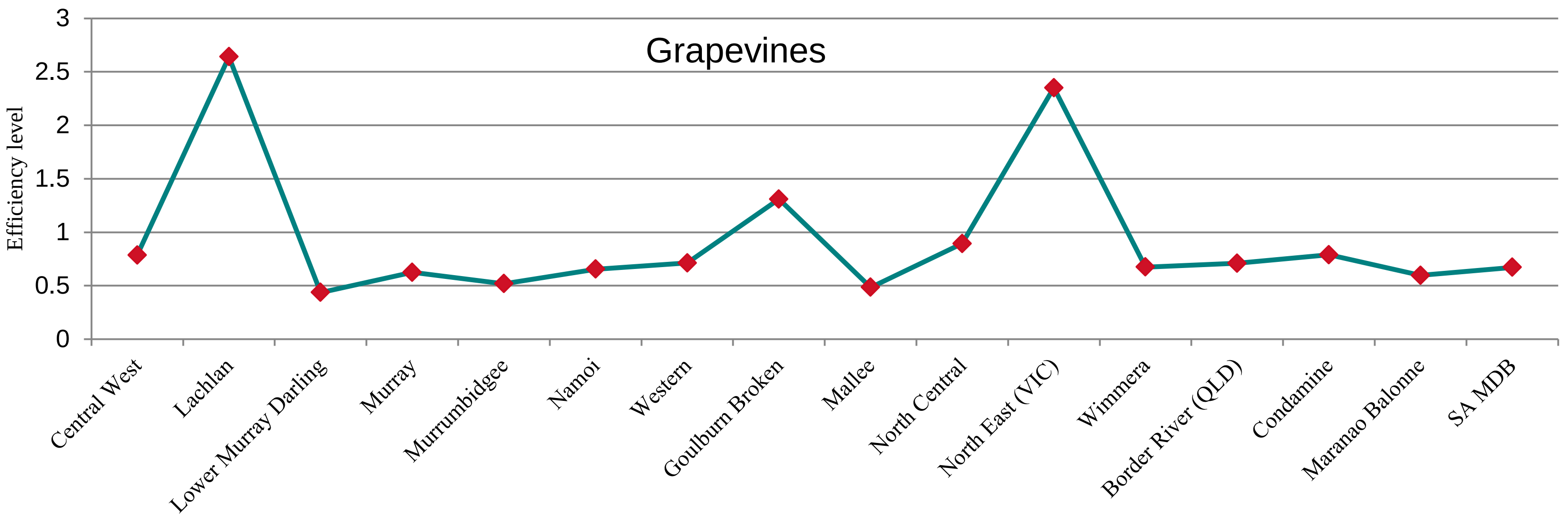

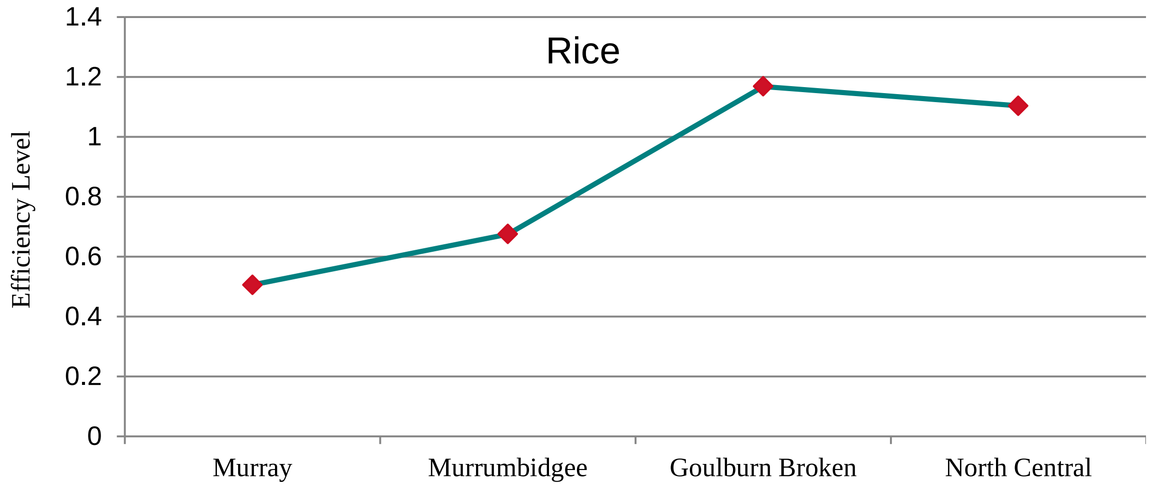

Conclusions

- Introduces a new productivity and efficiency measurement approaches: Luenberger environmental indicator
- The estimated environmental adjusted efficiencies of irrigated enterprises vary across regions.
- Environmental threats of irrigation water withdrawal in a specific region are largely dependent on both the existence and the significance of ecological assets.
- Regions that have an important Ramsar wetland and where a given irrigated enterprise takes out substantial amounts of irrigation water from the river system exert a greater environmental pressure.

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Conclusions

- Findings can be used to inform policies designed to stimulate exit of inefficient enterprises from those regions that are environmentally sensitive.
- The effect of such policies across NRM regions will help achieving sustainable water resource management.
- The Luenberger environmental indicator can be widely used in the agricultural sector and elsewhere in the economy to account for the effects of spatially attributable differences.