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

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7-9 September, 2014
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)
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
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 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).
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.
Consider a multi-output production technology:

- vector of inputs: \( x = (x_1, \ldots, x_N) \in \mathbb{R}_+^N \)
- desirable outputs: \( d = (d_1, \ldots, d_M) \in \mathbb{R}_+^M \)
- undesirable outputs: \( u = (u_1, \ldots, u_J) \in \mathbb{R}_+^J \)

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: \( g = (g_d, g_u) \)

› Directional distance function:

\[
\vec{D}_o(x, d, u; g_d, -g_u) = \sup \{ \beta : (d + \beta g_d, u - \beta g_u) \in P(x) \}.
\]

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:

\[
\vec{D}_o^a(x^a, d^a, u^a; g_d, -g_u) = \sup \{ \beta : (d^a + \beta g_d, u^a - \beta g_u) \in P^a(x^a) \}.
\]
\[ \text{LEI}_a^b = \frac{1}{2} [\overrightarrow{D}_o^b (x^a, d^a, u^a; g_d, -g_u) - \overrightarrow{D}_o^b (x^b, d^b, u^b; g_d, -g_u) + \overrightarrow{D}_o^a (x^a, d^a, u^a; g_d, -g_u) - \overrightarrow{D}_o^a (x^b, d^b, u^b; g_d, -g_u)] \]

If the value of \( \text{LEI}_a^b \) 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)

\[
LEI^b_a = \left[ \overline{D}_a^b(x^a, d^a, u^a; g_d, -g_u) - \overline{D}_b^b(x^b, d^b, u^b; g_d, -g_u) \right] + \frac{1}{2} \left[ \overline{D}_o^b(x^b, d^b, u^b; g_d, -g_u) - \overline{D}_a^a(x^a, d^a, u^a; g_d, -g_u) + \overline{D}_b^b(x^b, d^b, u^b; g_d, -g_u) - \overline{D}_o^a(x^a, d^a, u^a; g_d, -g_u) \right]
\]

efficiency variation

technological variation
Graphically

Comparison:
Observation N of region a
Observation S of region b

\[
EV = MN - RS \\
TV = \frac{1}{2} [ RS - ST + LN - MN]
\]

\[
\mathbb{F} = (g_d, g_u)
\]

Figure: The Luenberger environmental indicator
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**: 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 \(i\) \((i = 1, \ldots, 10)\) in \(j\) \((j = 1, \ldots, 17)\) 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: 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 \( j \)
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:

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

s.t. \[
\sum_{k=1}^{K} z_k^b d_{km}^b \geq d_{k,m}^{a} + \beta g_{dm} , \quad m = 1, \ldots, M \\
\sum_{k=1}^{K} z_k^b u_{kj}^b = u_{k,j}^{a} - \beta g_{uj} , \quad j = 1, \ldots, J \\
\sum_{k=1}^{K} z_k^b x_{kn}^b \leq x_{k,n}^{a} , \quad n = 1, \ldots, N \\
z_k^b \geq 0 , \quad k = 1, \ldots, K .
\]
## Table 1. Mean values of the economic and environmental variables of the production model

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

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

<table>
<thead>
<tr>
<th>NRM Regions</th>
<th>Cotton</th>
<th></th>
<th>Rice</th>
<th></th>
<th>Cereal crops for grain/seed</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEI</td>
<td>EV</td>
<td>TV</td>
<td>LEI</td>
<td>EV</td>
<td>TV</td>
</tr>
<tr>
<td>Border River-Gwydir</td>
<td>0.456</td>
<td>0.000</td>
<td>0.456</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Central West</td>
<td>0.340</td>
<td>0.425</td>
<td>-0.084</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lachlan</td>
<td>1.985</td>
<td>0.363</td>
<td>1.622</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lower Murray Darling</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Murray</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.505</td>
<td>0.261</td>
<td>0.244</td>
</tr>
<tr>
<td>Murrumbidgee</td>
<td>0.601</td>
<td>0.155</td>
<td>0.446</td>
<td>0.675</td>
<td>0.261</td>
<td>0.414</td>
</tr>
<tr>
<td>Namoi</td>
<td>0.800</td>
<td>0.425</td>
<td>0.376</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Western</td>
<td>0.728</td>
<td>0.425</td>
<td>0.304</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Goulburn Broken</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.168</td>
<td>-0.164</td>
<td>1.332</td>
</tr>
<tr>
<td>Mallee</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>North Central</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.103</td>
<td>0.261</td>
<td>0.842</td>
</tr>
<tr>
<td>North East (VIC)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wimmera</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Border River (QLD)</td>
<td>0.712</td>
<td>0.425</td>
<td>0.288</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Condamine</td>
<td>0.783</td>
<td>0.425</td>
<td>0.359</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Maranao Balonne</td>
<td>0.815</td>
<td>0.425</td>
<td>0.390</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*LEI = Luenberger environmental indicator, EV = Efficiency variation, TV = Technological variation.*
Table 2b. Values of the Luenberger environmental indicators for irrigated enterprises

<table>
<thead>
<tr>
<th>NRM Regions</th>
<th>Cereal crops cut for hay</th>
<th>Pasture for grazing</th>
<th>Pasture for hay and silage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEI</td>
<td>EV</td>
<td>TV</td>
</tr>
<tr>
<td>Border River-Gwydir</td>
<td>0.619</td>
<td>0.184</td>
<td>0.435</td>
</tr>
<tr>
<td>Central West</td>
<td>3.425</td>
<td>-0.067</td>
<td>3.492</td>
</tr>
<tr>
<td>Lachlan</td>
<td>0.327</td>
<td>-0.076</td>
<td>0.403</td>
</tr>
<tr>
<td>Lower Murray Darling</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Murray</td>
<td>0.315</td>
<td>-0.109</td>
<td>0.424</td>
</tr>
<tr>
<td>Murrumbidgee</td>
<td>0.448</td>
<td>-0.046</td>
<td>0.494</td>
</tr>
<tr>
<td>Namoi</td>
<td>1.091</td>
<td>-0.133</td>
<td>1.224</td>
</tr>
<tr>
<td>Western</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Goulburn Broken</td>
<td>0.236</td>
<td>-0.103</td>
<td>0.339</td>
</tr>
<tr>
<td>Mallee</td>
<td>0.650</td>
<td>0.000</td>
<td>0.650</td>
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<tr>
<td>North Central</td>
<td>0.051</td>
<td>-0.100</td>
<td>0.151</td>
</tr>
<tr>
<td>North East (VIC)</td>
<td>0.390</td>
<td>-0.013</td>
<td>0.403</td>
</tr>
<tr>
<td>Wimmera</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Border River (QLD)</td>
<td>2.659</td>
<td>-0.032</td>
<td>2.691</td>
</tr>
<tr>
<td>Condamine</td>
<td>1.618</td>
<td>-0.023</td>
<td>1.642</td>
</tr>
<tr>
<td>Maranao Balonne</td>
<td>1.149</td>
<td>-0.063</td>
<td>1.212</td>
</tr>
<tr>
<td>SA Murray Darling Basin</td>
<td>0.690</td>
<td>0.000</td>
<td>0.690</td>
</tr>
</tbody>
</table>

LEI = Luenberger environmental indicator, EV = Efficiency variation, TV = Technological variation.
### Table 2c. Values of the Luenberger environmental indicators for irrigated enterprises

<table>
<thead>
<tr>
<th>NRM Regions</th>
<th>Other broadacre crops</th>
<th>Vegetables</th>
<th>Fruit and nut trees</th>
<th>Grapevines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEI</td>
<td>EV</td>
<td>TV</td>
<td>LEI</td>
</tr>
<tr>
<td>Border River-Gwydir</td>
<td>0.454</td>
<td>-0.088</td>
<td>0.542</td>
<td>-</td>
</tr>
<tr>
<td>Central West</td>
<td>1.514</td>
<td>-0.716</td>
<td>2.230</td>
<td>0.210</td>
</tr>
<tr>
<td>Lachlan</td>
<td>0.403</td>
<td>0.000</td>
<td>0.403</td>
<td>2.697</td>
</tr>
<tr>
<td>Lower Murray Darling</td>
<td>1.360</td>
<td>0.000</td>
<td>1.360</td>
<td>1.033</td>
</tr>
<tr>
<td>Murray</td>
<td>0.064</td>
<td>-0.814</td>
<td>0.879</td>
<td>0.604</td>
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<tr>
<td>Murrumbidgee</td>
<td>0.671</td>
<td>-0.488</td>
<td>1.159</td>
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<tr>
<td>Namoi</td>
<td>0.787</td>
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<td>1.493</td>
<td>-</td>
</tr>
<tr>
<td>Western</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Goulburn Broken</td>
<td>0.330</td>
<td>0.000</td>
<td>0.330</td>
<td>2.181</td>
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<td>Mallee</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.491</td>
</tr>
<tr>
<td>North Central</td>
<td>0.296</td>
<td>-0.716</td>
<td>1.012</td>
<td>0.118</td>
</tr>
<tr>
<td>North East (VIC)</td>
<td>0.088</td>
<td>-0.688</td>
<td>0.776</td>
<td>1.260</td>
</tr>
<tr>
<td>Wimmera</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Border River (QLD)</td>
<td>1.889</td>
<td>0.000</td>
<td>1.889</td>
<td>0.226</td>
</tr>
<tr>
<td>Condamine</td>
<td>0.813</td>
<td>-0.627</td>
<td>1.440</td>
<td>0.777</td>
</tr>
<tr>
<td>Maranao Balonne</td>
<td>1.199</td>
<td>0.000</td>
<td>1.199</td>
<td>-</td>
</tr>
<tr>
<td>SA Murray Darling Basin</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.749</td>
</tr>
</tbody>
</table>

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

**Cotton**

- Efficiency level varies significantly across regions, with peaks in the Border River-Gwydir and Gwydir regions.

**Cereal crops for grain/seed**

- Efficiency levels also vary widely, with notable peaks in the Lower Murray Darling and Murray regions, and troughs in the Western and Mallee regions.
Efficiency variation across regions

Cereal crops cut for hay

Pasture for grazing
Efficiency variation across regions

Pasture for hay and silage

Other broadacre crops
Efficiency variation across regions

**Vegetables**

- Central West
- Lachlan
- Lower Murray
- Darling
- Murray
- Murrumbidgee
- Goulburn Broken
- Mallee
- North Central
- North East (VIC)
- Border River (QLD)
- Condamine
- SA MDB

**Fruits**

- Central West
- Lachlan
- Lower Murray
- Darling
- Murray
- Murrumbidgee
- Namoi
- Western
- Goulburn Broken
- Mallee
- North Central
- Wimmera
- Border River (QLD)
- Condamine
- SA MDB
Efficiency variation across regions

**Grapevines**

- Central West
- Lower Murray Darling
- Murray
- Murrumbidgee
- Namoi
- Western
- Goulburn Broken
- Mallee
- North Central
- North East (VIC)
- Wimmera
- Border River (QLD)
- Condamine
- Murray Balonne
- SA MDB

**Rice**

- Murray
- Murrumbidgee
- Goulburn Broken
- North Central
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.
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.