Climate Change and Dynamic Adjustment of Agricultural TFP: A Cross-regional Comparison of Broadacre Farms in Australia

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Introduction

• Climate change is believed to impose a profound impact on agricultural productivity.
  
  • Climate condition (i.e. rainfall and temperature) determines the long-term relationship between inputs and outputs;

  • Seasonal shocks deviate agricultural productivity away from its long-run trend;

• For decades, there has been a large amount of literature focusing on the impact of climate change

  • International level: Rosenzweig and Parry (1994), Mendelsohn and Dinar (1999), and Calzadilla et al. (2010)

  • National level: Olesen and Bindi (2002) for EU, Quiggin and Horowitz (2003) for Australia, Deschenes and Greenstone (2007) and ERS (2013) for US
Introduction

• These studies can be categorised into three groups in terms of methodology
  • Agronomic models
  • Agro-economic models
  • Ricardian models

• Most existing studies provide measures of climatic effects in the long run while they overlook the dynamic response of agricultural productivity to climatic shocks.
  • Even in cases where farmers’ adaptation was considered, the induced effects are hypothetically assumed;

• It is widely recognised that farmers’ adaptation behaviour in response to climatic shocks can significantly offset the climate impact (Darwin et al. 1995).
Introduction

• This study investigates the dynamics in the impact of climate change on agricultural productivity in Australian broadacre agriculture, by using the data from 32 regions between 1978 and 2013.

  • We distinguish the climate effects in the short run from those in the long run;

  • We quantity the adjustment of regional total factor productivity (TFP) towards the long-term equilibrium;

• Methodologically, we apply a vector error correction model to analyse the panel data (Pesaran et al., 1999; Im et al., 2003; Blackburne and Frank, 2007), accounting for regional heterogeneity, to

  • Identify the channels through which adaptation to climate change takes place;

  • Explore the disparity of adaptation process between farms using different production systems;
Introduction

• Our research contributes to the literature in three areas
  • To unravel the dynamic response of agricultural productivity to climatic shocks, and show the spatial pattern of these responses;
  • To investigate the channels through which region-level agricultural productivity adapts to climate change;
  • To provide a way to construct an agricultural production account at the regional level by using farm survey data;
• The findings of this study also provide an alternative explanation on cross-regional productivity disparity in a country, like Australia
  • the convergence analysis of agricultural productivity between regions: Ball et al. (1999), Acquaye et al. (2003), Ball et al. (2004) and Alston et al. (2015)
Background

- Broadacre agriculture is an important primary industry in Australia

  - The broadacre industry accounts for 1.9 per cent of GDP and 2.3 per cent of employment in 2015-16;

  - The industry covers all non-irrigated crop and livestock farms, accounting for around 70 percent of agricultural production;

  - Broadacre farms widely distribute throughout the country, and adopt different production systems in different locations;

  - Given the nature of broadacre agriculture, climate conditions heavily influence the productivity of the industry;

  - For simplicity, two aspects are addressed: water and temperature.
Figure 1: the distribution of broadacre production in Australia
Background

• Rainfall (or soil moisture)
  • Australia is a relatively dry continent and for broadacre agriculture, rainfall is the main source of soil moisture
    • Rainfall determines the growth of crops (i.e. wheat and barley etc.);
    • Rainfall also affects pastoral grassland and livestock production

• Air temperature
  • Temperature affects the growth of plant in different development stages, together with other climate factors such as water, CO2;
  • Temperature assists crop growth and livestock raising through a non-linear way, with extremely high temperature doing harm to farm production;
Background

• Over time, broadacre farms have demonstrated a remarkable adaptive capacity to cope with climate change.
  • A strong productivity growth of 2% a year over the long run;

• In practice, farmers can adapt to climate change through many alternative channels, e.g.
  • Change the production technology by optimising the use of capital and labor;
  • Adjust the output mixture to diversify the risk from climate change;

• Many adaptation activities require a significant amount of time and incur additional costs.
Empirical Model

• Region-level agricultural TFP is a function of various productivity determinants
  • climate condition including water availability and air temperature
  • regional specific characteristics and other control variables

\[ \ln TFP_{rt} = f_{rt}(W_{rt}, T_{rt}, Z_{rt}, F_r, F_t) + \varepsilon_{rt} \] (1)

• \( \ln TFP_{rt} \) is the logarithm of agricultural TFP at region \( r = (1, \ldots, R) \) and time \( t = (1, \ldots, T) \);

• \( W_{rt} \) and \( T_{rt} \) are a set of climate variables which capture the effects of climate change;

• \( Z_{rt} \) represent the control variables which consist of various macroeconomic and microeconomic factors;

• \( F_t \) and \( F_r \) are region and time specific effects;
Empirical Model

• If two conditions hold
  
  • Regional agricultural TFP and its determinants are integrated of order one I(1);
  
  • The error term is integrated of order zero I(0) for all regions;

\[
\Delta \ln TFP_{rt} = \phi_i[\ln TFP_{rt-1} - \theta'_{rt-1}(W_{rt}, T_{rt}, Z_{rt}, F_r, F_t)] + \\
\lambda_{rt}\Delta f_{rt}(W_{rt}, T_{rt}, Z_{rt}, F_r, F_t) + \varepsilon_{rt}
\]  

(2)

• $\phi_i$ is the error-correcting speed of adjustment term

• $\theta'_{rt}$ and $\lambda_{rt}$ are the long-term and the short-term effects of various productivity determinants
Empirical Model

![Graph of TFP response over time periods](image)
Empirical Model

• The estimated coefficients are used to quantify farmers’ adaptation behaviour
  
  • $\theta'_i$ and $\lambda_{rt}$ represent long-term and short-term climate effects;
  
  • $\phi_i$ captures the speed of farmers’ adjustment to the long-term equilibrium;
  
• The model is estimated by using the maximum likelihood method.
  
  • Both MG and PMG approaches can be applied;
  
  • The choice between the estimators from the two approaches is based on a Hausman test (Pesaran et al. 1999);

• The model is modified to examine potential channels for adaptation, by incorporating additional variables into the baseline regression.
Data Source

• The data used in this paper come mainly from four sources
  • Australian Agricultural and Grazing Industry Survey (AAGIS): regional TFP measures;
  • The Queensland University and the government of Queensland: soil moisture and air temperature;
  • The Census of Population and Housing from Australian Bureau of Statistics (ABS): general economic and social conditions;
  • The data for major variables are collected and compiled
    • at the farm level, or
    • at the shire/SLA levels
  and aggregated to the region level.
Data Source

• Region-level TFP Measure
  
  • TFP index is defined as the ratio of gross output over total inputs;
  
  • Outputs and inputs are aggregated using the Törnqvist-Theil index formulas;
  
  • The multilateral index formula suggested by Caves et al (1982) is employed to resolve the transitivity issue;
  
• The farm-level data obtained from AAGIS survey are used to construct the production account for broadacre agriculture.
  
  • 4 broad output categories (covering 13 types of commodities): crop, livestock, wool and “other farm income”;
  
  • 5 input categories (encompassing a total of 26 types of inputs): land, labour, capital, materials and services;
Data Source

- Water availability measure
  - The index is measured by using three agro-climatic indicators called “wheat water-stress index”, “sorghum water index” and “pasture growth index”.
  - The pasture growth index is also calculated based on a water balance model (Carter et al. 2000, Rickert et al. 2000).
  - We aggregate the indexes up to the regional level using land areas for cropping and grazing as weights.
    - The three indexes, in their original form, are annual time series defined at sub-regional (shire) level.
  - Total rainfall has also been used as a robustness check.
Figure 2 crop water-stress index
Data Source

- Two indicators are used to measure temperature / radiation:
  - degree-days accumulated over the growing seasons;
  - average daily temperature;
- A base of 8°C and a ceiling of 32°C are used as the temperature threshold (Schlenker et al., 2006 and Deschenes and Greenstone, 2007)
  - 1st April to 31st October for the winter season;
  - 1st November to 31st March for the summer season;
- The daily average temperature and rainfall are
  - obtained at the 8,023 weather stations of the Australian Bureau of Meteorology (BoM);
  - Matched with each farm in our survey;
Figure 3 weather information match
Empirical Results

• A descriptive statistics shows the relationship between region-level agricultural TFP and climate conditions.
  • There are monotonic relationship between water-stress index and regional TFP;
  • The relationship between degree-day measures and regional TFP is non-linear;

• Panel-data co-integration test has been conducted
  • I(1) stationary tests have been conducted for all variables used in the model
  • A co-integration relationship has been identified between region-level TFP and climate variables
Figure 4: The relationship between water-stress index and regional TFP
Figure 4 the relationship between degree-day measure and regional TFP
Table 1 Co-integration test results

<table>
<thead>
<tr>
<th>Region</th>
<th>Model</th>
<th>Gt Test Statistics</th>
<th>Gt Test P-value</th>
<th>Pt Test Statistics</th>
<th>Pt Test P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Regions</td>
<td>include climate variables (Model I)</td>
<td>-2.38</td>
<td>0.00</td>
<td>-11.74</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Include all variables (Model II)</td>
<td>-3.23</td>
<td>0.00</td>
<td>-14.23</td>
<td>0.01</td>
</tr>
<tr>
<td>High-rainfall Zone</td>
<td>include climate variables (Model I)</td>
<td>-2.88</td>
<td>0.00</td>
<td>-7.66</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Include all variables (Model II)</td>
<td>-3.39</td>
<td>0.00</td>
<td>-9.33</td>
<td>0.00</td>
</tr>
<tr>
<td>Wheat-sheep Zone</td>
<td>include climate variables (Model I)</td>
<td>-2.76</td>
<td>0.00</td>
<td>-7.73</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Include all variables (Model II)</td>
<td>-3.20</td>
<td>0.01</td>
<td>-9.73</td>
<td>0.02</td>
</tr>
<tr>
<td>Pasture Zone</td>
<td>include climate variables (Model I)</td>
<td>-2.97</td>
<td>0.00</td>
<td>-7.81</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Include all variables (Model II)</td>
<td>-3.18</td>
<td>0.02</td>
<td>-9.51</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Empirical Results

• There is a significant long-term relationship between climate condition and region-level agricultural productivity.

  • Water availability positively contributes to regional TFP growth in the long run;

  • Degree-days will positively contribute to regional TFP initially but its marginal contribution tends to decline when the degree-day measure reach a threshold;

• In the short run, water availability also generate the short-term volatility in agricultural productivity

• Region-level agricultural TFP will gradually returns to the long-term equilibrium value

  • the estimated error correction coefficient is negative and significant at 1 per cent level.
### Table 2: Climate change and its impact on region-level agricultural productivity

<table>
<thead>
<tr>
<th></th>
<th>Baseline Model (Model I)</th>
<th>Full Model (Model II)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EC</td>
<td>SR</td>
</tr>
<tr>
<td>Dependent variable: regional-level agricultural TFP (log)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water-stress index (log)</td>
<td>2.279***</td>
<td>0.244**</td>
</tr>
<tr>
<td></td>
<td>(0.268)</td>
<td>(0.108)</td>
</tr>
<tr>
<td>Growing season degree-days</td>
<td>1.886**</td>
<td>7.74</td>
</tr>
<tr>
<td></td>
<td>(0.817)</td>
<td>(6.422)</td>
</tr>
<tr>
<td>Growing season degree-days (log) square</td>
<td>-0.153**</td>
<td>-0.542</td>
</tr>
<tr>
<td></td>
<td>(0.064)</td>
<td>(0.444)</td>
</tr>
<tr>
<td>SEFA index (log)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proportion of operators with primary school or less education level</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Farm Size - land areas (log)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error Correction Coefficient</td>
<td>-</td>
<td><strong>0.340</strong>*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.032)</td>
</tr>
<tr>
<td>Constant</td>
<td>-</td>
<td>-2.180***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.213)</td>
</tr>
</tbody>
</table>
Empirical Results

- Farmers adapt to climate change through particular channels
  - The capital-labor ratio is more likely to play a role in the long run;
  - The output mixture is more likely to play a role in the short run;
- Impacts of the afore-mentioned two channels differ between farms using different production systems
  - Adjustment speed in the high rainfall zone is much quicker than in wheat-sheep zone and pasture zone;
  - Impact of water stress on agricultural production in the long run still exists, even if full adaptation behaviours have been taken into account;
  - Agricultural TFP is more vulnerable to climatic shocks in the pasture zone than in the high-rainfall zone and in the wheat-sheep zone;
**Table 3 dynamic impact of climate change on agricultural TFP by Zone**

<table>
<thead>
<tr>
<th></th>
<th>All Zones</th>
<th>High-rainfall Zone</th>
<th>Wheat-sheep Zone</th>
<th>Pasture Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EC</td>
<td>SR</td>
<td>EC</td>
<td>SR</td>
</tr>
<tr>
<td>Dependent variable: regional-level agricultural TFP (log)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water-stress index (log)</td>
<td>1.678***</td>
<td>-0.111</td>
<td>1.534**</td>
<td>-0.48</td>
</tr>
<tr>
<td></td>
<td>(0.327)</td>
<td>(0.144)</td>
<td>(0.605)</td>
<td>(0.299)</td>
</tr>
<tr>
<td>Growing season degree-days</td>
<td>1.598</td>
<td>1.875</td>
<td>1.527</td>
<td>1.179</td>
</tr>
<tr>
<td>Growing season degree-days (log) square</td>
<td>-0.121</td>
<td>-0.101</td>
<td>-0.138</td>
<td>-0.024</td>
</tr>
<tr>
<td></td>
<td>(0.121)</td>
<td>(0.569)</td>
<td>(0.297)</td>
<td>(1.439)</td>
</tr>
<tr>
<td>SEFA index (log)</td>
<td>1.165**</td>
<td>0.947**</td>
<td>1.505</td>
<td>2.544***</td>
</tr>
<tr>
<td></td>
<td>(0.518)</td>
<td>(0.401)</td>
<td>(1.048)</td>
<td>(0.809)</td>
</tr>
<tr>
<td>Proportion of operators with primary school or less education level</td>
<td>-1.706***</td>
<td>-0.306**</td>
<td>-0.650***</td>
<td>-0.08</td>
</tr>
<tr>
<td></td>
<td>(0.516)</td>
<td>(0.147)</td>
<td>(0.227)</td>
<td>(0.143)</td>
</tr>
<tr>
<td>Average Farm Size - land areas (log)</td>
<td>0.135*</td>
<td>0.02</td>
<td>0.014</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>(0.081)</td>
<td>(0.043)</td>
<td>(0.108)</td>
<td>(0.065)</td>
</tr>
<tr>
<td>Capital-labour ratio (log)</td>
<td>-0.294***</td>
<td>-0.001</td>
<td>-0.162</td>
<td>0.043</td>
</tr>
<tr>
<td></td>
<td>(0.107)</td>
<td>(0.042)</td>
<td>(0.170)</td>
<td>(0.071)</td>
</tr>
<tr>
<td>Crop-livestock mixture</td>
<td>0.055</td>
<td>0.043**</td>
<td>0.07</td>
<td>-0.026</td>
</tr>
<tr>
<td></td>
<td>(0.035)</td>
<td>(0.020)</td>
<td>(0.052)</td>
<td>(0.029)</td>
</tr>
<tr>
<td>Error Correction Coefficient</td>
<td>-</td>
<td>-0.728***</td>
<td>-0.834***</td>
<td>-0.712***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.048)</td>
<td>(0.054)</td>
<td>(0.094)</td>
</tr>
<tr>
<td>Constant</td>
<td>-</td>
<td>-3.676***</td>
<td>-</td>
<td>6.583</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4.306)</td>
<td>(12.863)</td>
<td>(71.385)</td>
</tr>
</tbody>
</table>
Figure 1: The distribution of broadacre production in Australia.
Figure 5 speed of adjustment across regions: 1978-2013
Robustness checks

- Region-level TFP is re-measured by using an alternative index formulas
  - The Fisher index adjusted by the EKS formula is used instead;

- Climate variables are re-defined by directly using
  - the total rainfall over the growing season
  - the daily average temperature over the growing season

- Stability of the PECM model has been double-checked.
Conclusions

• We investigate the dynamic impact of climate change on agricultural TFP in Australia through
  • Using a vector error correction model to the panel data;
  • Allowing for regional heterogeneity and other control variables;
• Climate change generates a complex impact on agricultural productivity across regions
  • In the long run, water availability and temperature
  • In the short run, water availability matters more
• Farmers are able to adopt to climate change through
  • Optimising the capital-labor ratio;
  • Adjusting the output mix
Questions and Comments