

# **Evaluating the climatic impacts on dryland crop growth using multi-source datasets across Australia**

A Dissertation Presented

by

**Jianxiu Shen**

Submitted to University of Technology Sydney  
in partial fulfillment of the requirements for the degree of

**Doctor of Philosophy**



February 2019

## **Certificate of Original Authorship**

I, Jianxiu Shen, certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student:      Production Note:  
   Signature removed prior to publication.

Date: 03-02-2019

This research is supported by an Australian Government Research Training Program Scholarship.

## **Acknowledgement**

The past four years have been a challenging but rewarding journey for me. My son was born in the last year of my PhD, which has placed an extra load during the extreme stressed time of period. After some struggling, I finally managed to find the balance between PhD and my life. This experience has not only enabled me to discover a more patient, self-discipline and high-efficiency me I never thought of, but also taught me how to be a good independent researcher and a good independent mum. At the end of this journey, I am so much indebted to the people who has encouraged and supported me.

I would like to thank my principal supervisor professor Qiang Yu, co-supervisor distinguished Professor Alfredo Huete for their supervision during my PhD. Professor Qiang Yu has given me great support to apply for the scholarship to pursue my PhD at such a dynamic and forward-looking university. He has always respected my thoughts, allowed me the freedom to practice whatever interested me, and encouraged me to publish the research findings throughout the whole period. Professor Alfredo Huete has always given me time and showed genuine interest in my idea. Talking and discussing with him always provided me with a source of guidance and much needed comfort and confidence. Also, I am very grateful for him offered me the opportunities to get involved in his research lab, access to all the group resources, and get involved in teaching as a tutor. I am lucky to have the expertise and kindness from both Qiang and Alfredo.

I am also indebted to professor Derek Eamus for reading through my multiple drafts and inspiring me to keep going on with my work. I am thankful to Dr. Rakesh Devadas, Dr. Longhui Li and Dr. Natalia Restrepo Coupe for their helpful suggestions in strengthening both the theoretical and technological aspect of my work during the initial stages of my

PhD. Acknowledgement also goes to Dr. Xuanlong Ma, who has offered me much advice beneficial to my academic research.

I would like to thank Ann-Maree Dombroski, who is one of my INSEARCH teacher, not only for her help in improving my academic English skills, but also for her true caring as a friend afterwards. I also thank my PhD friends, who generously offered their time and support, including Dr. Zunyi Xie, Dr. Hao Shi, Nguyen Ngoc Tran, Dr. Xueling Li, Dr. Xunhe Zhang, Dr. Bin Wang, Dr. Wenbo Wang, Qinggaozi Zhu, Dr. Buddhi Dayananda, Dr. Rolanda Lam, Dr. Leandro Giovannini, Paras Sidiqui, Ekena Rangel Pinage, Marita Gambino, Jie He, Wenjie Zhang, Sicong Gao, Jiaqi Dong, Rong Gan, Wanxin Chen, Rui Wang, Li Huang, Jingyan Zhang, Dr. Arjun Verma and Lorenzo Barolo. I am grateful to the staff and research fellows in the first Australian Energy and Water Exchange initiative (OzEWEX) Climate and Water Summer Institute, especially Professor Albert van Dijk, Dr. Mohammad Azmi, Dr. Siyuan Tian and Chinchu Mohan, sharing with me much valuable inspirations and joys memorable to my life.

I acknowledge the financial support received from International Research Scholarships, University of Technology Sydney, Australia, and the Chinese Scholarship Council, Ministry of Education, China. I am grateful to consular Jing Zhao and Wenwu Liu from the education office, the consulate general of P.R.China in Sydney for gathering the Chinese scholars regularly and providing me much supportive information and resources. I am thankful to Shannon Hawkins, Maggie Chen, Alex Chen, Emaly Black and the staff from UTS Graduate Research School for their administrative assistance and considered advice, which ensured me had a pleasant study experience throughout my PhD. I appreciate the priceless study resources and workshops provided from both on-campus

and off-campus. I also would like to thank the UTS library for providing additional peaceful environment and necessary infrastructure during the writing of my thesis.

Last but not least, I would like to thank my partner Dr. Mingming Cheng, who has always pushed me to step out of my comfort zone and encouraged me to carry on step by step and to challenge myself to be better. I also would like to thank my father (Fulin Shen) and elder sisters (Jianju Shen and Jianchun Shen) in China for their understanding and encouragement. They have always tried their best unconditionally to help me out of difficulties. Special thanks go to my son Xinqi Cheng, who has fully trusted in me and forgave all my unintended carelessness. Your smile has made me appreciate life and time so much. Thank you for being a part of my life and thank you for being you. love you!

The whole thesis is dedicated to the memory of my mother, Lianxiang Liu, who has been so proud of her three brave daughters. Your belief in me has made this journey possible. Words just can't describe how much I miss you, mom...

## **Publications arising from this thesis**

### *Journal papers directly included in this thesis*

Shen, J., Huete, A., Tran, N.N., Devadas, R., Ma, X., Eamus, D. & Yu, Q. 2018, 'Diverse sensitivity of winter crops over the growing season to climate and land surface temperature across the rainfed cropland-belt of eastern Australia', *Agriculture, Ecosystems & Environment*, vol. 254, pp. 99-110. (Chapter 4)

Shen, J., Huete, A., Tran, N.N., Ma, X., Joiner, J., Beringer, J., Eamus, D. & Yu, Q. 2019, 'Dynamics of light-use efficiency using satellite solar-induced chlorophyll fluorescence and the enhanced vegetation index across Australian rainfed croplands'. (Under review) (Chapter 5)

Shen, J., Huete, A. & Yu, Q. 2019, 'Dryland climate-crop growth relationship: a Review' (Under review) (Chapter 2)

### *Parts of the journal paper arising from this thesis*

Azmi, M., Shen, J., Mohan, C., Dijk, A. 2019, 'Spatiotemporal prediction of rainfed grain annual yield across Australia based on soil moisture and gross primary production estimates'. (Under Review) (Chapter 3)

### *Peer-reviewed conference proceedings*

1. Shen, J., Huete, A., Tran, N.N., Ma, X. & Yu, Q. 2017, 'Detecting the response of seasonal light-use efficiency to canopy temperature by using satellite solar-induced chlorophyll fluorescence and enhanced vegetation index across Australian rainfed croplands', *American Geophysical Union Fall Meeting (AGU)*, New Orleans, Louisiana, U.S.A, 11-15 December.

2. Shen, J., Huete, A., Ngoc, T.N., Devadas, R. & Yu, Q. 2016, 'Incorporating remote sensing methods into crop-climate relationships across the rain-fed cropland belt in NSW, Australia', *The Australian energy and water exchange research initiative National workshop*, Canberra, Australia, 14-15 December.

3. Shen, J., Tran, N.N., Devadas, R., Huete, A., Zhang, H. & Yu, Q. 2016, 'Climate impacts on wheat phenology and production using multi-source data in NSW, Australia', *Geoscience and Remote Sensing (IGARSS), IEEE International Symposium*, Beijing, China, pp. 6296-99. 10-15 July.

## Contents

<b>Certificate of Original Authorship</b> .....	I
<b>Acknowledgement</b> .....	II
<b>Publications arising from this thesis</b> .....	VI
<b>Contents</b> .....	VII
<b>Content of Figures</b> .....	XI
<b>Content of Tables</b> .....	XIII
<b>Abstract</b> .....	1
<b>Key words</b> .....	2
<b>Chapter 1. Introduction</b> .....	3
<b>1.1 Background</b> .....	3
1.1.1 Global climate change and variability .....	3
1.1.2 Climate trends and variability in Australia .....	4
1.1.3 Agricultural land use in Australia .....	6
<b>1.2 Incorporating multi-source datasets in climate-crop relationship analysis</b> .....	8
1.2.1 Weather patterns derived from SILO and sowing and harvesting windows from NVT .....	10
1.2.2 EVI time series profile of wheat phenology at different agro-climate zones.....	12
1.2.3 Spatial temporal relationship between climate factors and crop growth .....	13
<b>1.3 Significance</b> .....	14
<b>1.4 Structure of this thesis</b> .....	15
<b>References</b> .....	19
<b>Chapter 2. Dryland climate-crop growth relationship: a Review</b> .....	22
<b>Highlights</b> .....	22
<b>Abstract</b> .....	22
<b>Key Words</b> .....	22
<b>2.1 Introduction</b> .....	23
<b>2.2 Research design</b> .....	25
2.2.1 bibliographic analysis .....	25
2.2.2 Content analysis .....	26
<b>2.3 Main findings</b> .....	27
2.3.1 Bibliographic analysis results .....	27
2.3.1.1 Agro-climatic change variables .....	27



2.3.1.2 Crop growth measurements .....	30
2.3.1.3 Models employed in current CCR research .....	33
2.3.2 Content analysis results.....	35
2.3.2.1 Climate change/variability .....	36
2.3.2.2 Crop response.....	37
2.3.2.3 CCR approaches.....	37
2.3.2.4 Agricultural adaptation .....	39
<b>2.4 Discussion.....</b>	<b>39</b>
2.4.1 Integrated climate driving factor employment .....	40
2.4.2 Crop phenology and photosynthesis response focus.....	41
2.4.3 Multiple source of datasets engagement .....	41
2.4.4 Bottom-up approaches for agricultural adaptation.....	43
<b>2.5 Conclusions .....</b>	<b>43</b>
<b>Appendix .....</b>	<b>45</b>
<b>References .....</b>	<b>48</b>
<b>Chapter 3. Spatial prediction of rainfed grain yield based on remote sensing gross primary production estimates.....</b>	<b>55</b>
<b>Highlights.....</b>	<b>55</b>
<b>Abstract.....</b>	<b>55</b>
<b>Key Words .....</b>	<b>55</b>
<b>3.1 Introduction.....</b>	<b>56</b>
<b>3.2 Study area and data processing .....</b>	<b>59</b>
3.2.1 Study area.....	59
3.2.2 Grain annual yield.....	60
3.2.3 Monthly Gross Primary Production product.....	61
<b>3.3 Methodology .....</b>	<b>61</b>
<b>3.4 Results and Discussion.....</b>	<b>62</b>
3.4.1 Correlation between GPP and agricultural annual yield in Australia .....	62
3.4.2 Model development using Monthly GPP to forecast Annual yield .....	66
<b>3.5 Conclusion .....</b>	<b>67</b>
<b>References.....</b>	<b>69</b>
<b>Chapter 4. Diverse sensitivity of dryland winter crops over the growing season to climate and land surface temperature.....</b>	<b>72</b>
<b>Highlights.....</b>	<b>72</b>
<b>Abstract.....</b>	<b>72</b>
<b>Key Words .....</b>	<b>73</b>

<b>4.1 Introduction</b> .....	73
<b>4.2 Materials and Methods</b> .....	77
4.2.1 Study area.....	77
4.2.2 Data processing.....	79
4.2.2.1 Meteorological data and study sites.....	79
4.2.2.2 Remote sensing and in-situ datasets.....	79
4.2.2.3 Phenology metrics detection.....	81
4.2.3 Methodology.....	81
4.2.3.1 Variability indicator.....	81
4.2.3.2 Thermal time reference.....	82
4.2.3.3 Relative importance approach.....	83
<b>4.3 Results</b> .....	84
4.3.1 Crop growth seasonality and variability across the NSW wheat belt 2001 - 2013....	84
4.3.1.1 Crop growth seasonality and variability.....	84
4.3.1.2 The key 8-day time segment of the crop growth cycle.....	86
4.3.2 Climate and LST seasonality and variability across the NSW wheat-belt in growing season.....	87
4.3.2.1 Climate and LST seasonality and variability.....	87
4.3.2.2 Spatial variation of the 13-year average iEVI and climate conditions.....	90
4.3.3 Contributions of climate and LST variability to crop growth variation over the GS.	91
4.3.3.1 Individual impacts of climate and LST on EVI variation at a regional scale....	91
4.3.3.2 Accumulated relative contributions of the climate variability to the EVI variability.....	93
4.3.3.3 Spatial distribution of the climate and LST variability contributions to EVI variation.....	95
<b>4.4 Discussion</b> .....	96
4.4.1 Ability of the MODIS EVI profile to represent rainfed cropland productivity in Australia.....	96
4.4.2 Impacts of climate and LST variability on the variation of the EVI in key crop growth stages.....	99
<b>4.5 Conclusions</b> .....	100
<b>References</b> .....	103
<b>Chapter 5. Dynamics of light-use efficiency using satellite solar-induced chlorophyll fluorescence and the enhanced vegetation index</b> .....	109
<b>Highlights</b> .....	109
<b>Abstract</b> .....	109
<b>Key words</b> .....	110

<b>5.1 Introduction</b> .....	110
<b>5.2 Material and methods</b> .....	113
5.2.1 Obtaining LUE from SIF and EVI.....	113
5.2.2 Statistical analyses .....	114
5.2.3 Applications across Australian croplands .....	115
5.2.3.1 Land use classification .....	116
5.2.3.2 Satellite SIF retrievals.....	117
5.2.3.3 MODIS EVI and LST datasets.....	117
5.2.3.4 Eddy flux sites.....	118
5.2.3.5 Spatial division of testing pixels .....	120
5.2.3.6 Temporal division of testing pixels.....	120
<b>5.3 Results and Discussion</b> .....	121
5.3.1 Footprint calibration for flux sites .....	121
5.3.2 Spatial pattern of satellite-based vegetation measurements.....	123
5.3.3 Seasonal dynamics of LUE and related measurements.....	125
5.3.4 Performance of satellite based LUE in response to LST .....	127
<b>5.4 Conclusions</b> .....	133
<b>5.5 Limitation and future research</b> .....	134
<b>References</b> .....	137
<b>Chapter 6. Summary and future research</b> .....	142
<b>6.1 Summary</b> .....	142
<b>6.2 Contributions</b> .....	144
<b>6.3 Limitations and future research</b> .....	145

## Content of Figures

<b>Figure 1.1</b> Global year-to-year wheat yield variability over the last three decades (1979-2008) (left) and total wheat yield variability explained due to climate variability (right) .....	3
<b>Figure 1.2</b> Trends in total rainfall (A, mm/10yr), maximum temperature (B, °C/10yr), minimum temperature (C, °C/10yr), and mean temperature (D, °C/10yr) from 1970 to 2017 in Australia.....	4
<b>Figure 1.3</b> Normal Density curves of the historical climate conditions across Australian cropland .....	5
<b>Figure 1.4</b> Boxplots of de-trended crop yield (kg/ha; Wheat, Potatoes, Oats, Maize, and Barley) from 1877 to 2011 .....	7
<b>Figure 1.5</b> Comparison of weather conditions and sowing and harvest windows across NSW wheat belt in year 2005 and 2006 .....	11
<b>Figure 1.6</b> Wheat phenological smoothed EVI profile over different Agro-climate zones (E4, E3, E2, and D5).....	12
<b>Figure 1.7</b> Rainfall, hot days, growing season iEVI and sowing and harvest windows of crops across NSW wheat belt in 2005-2014.....	14
<b>Figure 1.8</b> Outline of the thesis .....	16
<b>Figure 2.1</b> scheme of efforts in ‘modelling’ from the 47 selected studies .....	33
<b>Figure 2.2</b> Conceptual map of CCR literature published during 2009-2018. ....	35
<b>Figure 3.1</b> Australian rainfed cropping and pasture land use belt (left) and Australian major climate zones based on Köppen classification (right).....	60
<b>Figure 3.2</b> Bootstrapping method to estimate model coefficients.....	62
<b>Figure 3.3</b> Correlation matrixes between annual-mean GPP and ABS annual yields.....	63
<b>Figure 3.4</b> Correlation matrixes between monthly-mean GPP and ABS annual yield .....	64
<b>Figure 4.1</b> Spatial distribution of the NSW rainfed cropland belt and locations of selected testing pixels .....	78
<b>Figure 4.2</b> Variation and trend of the average seasonal EVI profile in the NSW rainfed cropland belt from 2001 to 2013 and correlations of the 8-day EVIs with observed annual grain yield ..	85
<b>Figure 4.3</b> Growing season climate and LST seasonality as well as their variability and trend at each 8-day time segment from 2001 to 2013 across the NSW cropland belt .....	88

<b>Figure 4.4</b> Spatial variations of the 13-year average iEVI as well as growing season climate and LST conditions.....	91
<b>Figure 4.5</b> Partial correlations between standardized anomalies (Sa-s) of 8-day EVI and individual climate components in the growing seasons from 2001 to 2013 .....	92
<b>Figure 4.6</b> Individual and accumulated contributions of the climate and LST variability to the variation of EVI at the 8-day time scale in the growing season over 13 years .....	94
<b>Figure 4.7</b> Spatial distributions of the contributions of climate and LST standard anomalies (Sa-s) to EVI Sa-s in the growing season across the NSW cropland belts .....	96
<b>Figure 4.8</b> Scatterplots between the actual yield and iEVI for 117 trial sites and their linear regression lines.....	98
<b>Figure 5.1</b> Australian rainfed croplands in different levels of spatial resolution (left) and the spatial groups of testing pixels (right).....	116
<b>Figure 5.2</b> Flux tower footprint calibrations .....	122
<b>Figure 5.3</b> Spatial patterns in 10-year mean seasonality of LST, EVI, SIF <sub>PAR</sub> , and LUE.....	124
<b>Figure 5.4</b> Re-grouped spatial-temporal LST levels within each month divided by one-way ANOVA and <i>post hoc</i> test .....	130
<b>Figure 5.5</b> Spatial-temporal distributions of pixels with the re-grouped LST levels during August across all 10 years.....	131

## Content of Tables

<b>Table 1.1</b> NSW wheat planting area, yield and Sowing and Harvest windows in selected years .....	11
<b>Table 2.1</b> List of agro-climatic indicators used in selected Climate-Crop research literature ...	28
<b>Table 2.2</b> List of crop growth measurements used in selected Climate-Crop research literature .....	31
<b>Table 2.3</b> Themes and Concepts of CCR literature published during 2009-2018.....	36
<b>Table 2.4</b> Co-occurrence likelihood $\geq 20\%$ of related-concepts to ‘model’ .....	38
<b>Appendix</b> .....	45
<b>Table 3.1</b> Cereal yield models for three States.....	66
<b>Table 4.1</b> Seasonal climate and LST conditions each year across the rainfed cropland in NSW .....	89
<b>Table 5.1</b> Details of the three Australian eddy flux sites .....	119
<b>Table 5.2</b> Statistical summary of satellite based LST, EVI, SIF and LUE across all sites during the growing season.....	125
<b>Table 5.3</b> Pairwise comparison among each month for satellite based LST, EVI, SIF and LUE .....	126
<b>Table 5.4</b> Statistical summary of spatial-temporal percentage quantile LST levels each month from June to November .....	129

## **Abstract**

The rainfed cropland belt in Australia is of great importance to the world grain market but has the highest climate variability of all such regions globally. This thesis aims to quantify the spatial temporal climatic impacts on crop productivity, crop phenology and cropland photosynthesis activities across the Australian rainfed cropland belts using multiple source of observed datasets.

The literature review on climate-crop growth relationship called for a future agenda on integrated climate driving factor employment, crop phenology and photosynthesis response focus, multiple source of datasets engagement, and bottom-up approaches for agricultural adaptation. Consistent findings from the three empirical studies in this thesis, which focused on different broad angles of the crop response, indicate that: (1) August and September are the optimum trigger months to spatially predict agricultural annual yield across the rainfed cropland belts in Australia; (2) two critical 8-day periods, beginning on day of the year (DoY) 257 (in September) and 289 (in October), were identified as the key 'windows' of crop growth variation that arose from the variability in climate and land surface temperature. (3) there was a seasonal hysteresis of crop photosynthesis activities in response to surface temperature change throughout the winter crop growing season in Australia. The optimum surface temperature range for satellite observed photosynthesis activity were identified as 16.6-17.6 °C during August.

This thesis systematically assessed the climatic impacts on crop growth across the Australian rainfed cropland belts. Practically, it provides new opportunities for large-scale cropland heat and water stress detection and can serve as an early warning system

for agricultural adaptation in broad-acre rainfed cropping practices. Theoretically, it offers a fresh understanding for analyses of the climate-crop growth relationship across diverse spatial-temporal scales.

### **Key words**

Climate change and variability, crop growth, rainfed croplands, multi-source datasets, remote sensing, Australia