Modelling impacts of climate and weather extremes on wheat cropping systems across New South Wales

Puyu Feng

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

School of Life Sciences, Faculty of Science

University of Technology Sydney

Australia

May 2020

Certificate of Original Authorship

I, Puyu Feng declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Life Sciences/Faculty of Sciences at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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

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

Date: 21 May 2020

Acknowledgement

Undertaking this PhD is a challenging but life-changing experience for me. It would not have been possible to reach the ending point without the support and guidance that I received from many people.

First and foremost, I would like to express my sincere gratitude to my principal supervisor Professor Qiang Yu. It was him who encouraged me to pursue PhD at University of Technology Sydney and helped me apply for scholarships. It was also him who suggested me to conduct cooperative research at Wagga Wagga agricultural institute, New South Wales Department of Primary Industries (NSW DPI). His professional guidance as well as general support and encouragement helped me in all the time of research.

I would like to express my special appreciation and thank to my co-supervisor, principal research scientist Dr. De Li Liu, who provided me the chance to study at NSW DPI. During the four years in NSW DPI, Dr. De Li Liu has always been holding me to a high research standard by providing insightful comments on my work and constructive criticisms at different stages of my PhD study. I could not have imagined having a better advisor and mentor for my PhD study. His enthusiasm and rigorous manner for scientific research affects deeply on me and will have profound impact on my future career.

I am deeply grateful to Dr. Bin Wang at NSW DPI. He has been acting as a trustworthy brother, a responsible colleague, and an awe-inspiring teacher during my 4-year PhD study. Whenever I meet with difficulties, no matter from work or life, he is always there, ready to help me. He leads me into an amazing world of science and without his step-by-step guidance, insightful criticisms, constructive suggestions as well as constant encouragements, I could not make it to this point. His guidance plays a key role in the completion of this thesis.

I thank my fellows from UTS, Lijie Shi, Mingxi Zhang, Hong Zhang, Siyi Li, Dr. Jie He, Dr. Rong Gan, Dr. Qinggaozi Zhu, and Dr. Jianxiu Shen and fellows or visiting scholars from NSW DPI, Dr. Hongtao Xing, Dr. Xiaojun Shen, Dr. Hongyan Ruan, Dr. Yue Chen, Dr. Weiwei Xiao, Dr. Dengpan Xiao, for the kindness in your hearts, for the encouragement and support, , and for all the memorable happy and difficult time we share. I am thankful to my co-authors, Dr. Cathy Waters, Dr. Fei Ji, Dr. Ian Macadam, for their tremendous efforts in improving the early manuscripts that have been published. I am also grateful to staff in UTS and NSW DPI for their administrative assistance in various ways, which ensured a pleasant environment and convenient workflow during my PhD study.

I would especially like to thank my parents, my father Guangzhi Feng and my mother Guiling Wang, who supported my PhD study and always encourage and help me out of difficulties. I am the only child to my parents. It has been hard to them since I decided to study overseas four years ago, but they still supported me without a word of complaints.

Most importantly, I would like to thank my beloved partner Ting Li. I feel so sorry that I left China without a word four years ago and keep you waiting alone. If it weren't for me, you would have a man to accompany you and live a happier life. You chose to keep our long-distance relationship with a virtual boyfriend by video call. You have always been standing by me through all my travails, giving me unconditional support, sharing my smiles and tears during this journey. Now, we make it and we survive the long-distance. I owe you everything and will keep you in my love throughout my rest life.

I wish to gratefully acknowledge that the Chinese Scholarship Council provided the scholarship and the NSW DPI provided facilities for conducting this work.

Publications arising from this thesis

Journal papers directly included in this thesis

Feng, P., Wang, B., Liu, D.L., Xing, H., Ji, F., Macadam, I., Ruan, H. and Yu, Q., 2018. Impacts of rainfall extremes on wheat yield in semi-arid cropping systems in eastern Australia. Climatic change, 147(3-4), pp.555-569. (Chapter 2)

Feng, P., Wang, B., Liu, D.L. and Yu, Q., 2019. Machine learning-based integration of remotely-sensed drought factors can improve the estimation of agricultural drought in South-Eastern Australia. Agricultural Systems, 173, pp.303-316. (Chapter 3)

Feng, P., Wang, B., Liu, D.L., Waters, C., Xiao, D., Shi, L., and Yu, Q., 2019. Dynamic wheat yield forecasts are improved by a hybrid approach using a biophysical model and machine learning technique. Agricultural and Forest Meteorology, 285: 107922. (Chapter 4)

Feng, P., Liu, D.L., Wang, B., Waters, C., Zhang, M. and Yu, Q., 2019. Projected changes in drought across the wheat belt of southeastern Australia using a downscaled climate ensemble. International Journal of Climatology, 39(2), pp.1041-1053. (Chapter 5)

Feng, P., Wang, B., Liu, D.L., Waters, C. and Yu, Q., 2019. Incorporating machine learning with biophysical model can improve the evaluation of climate extremes impacts on wheat yield in south-eastern Australia. Agricultural and Forest Meteorology, 275, pp.100-113. (Chapter 6)

Peer-reviewed International Conference proceedings

Feng, P., Wang, B., Liu, D.L., Waters, C., Xiao, D., Shi, L., and Yu, Q., 2019. Developing a machine learning-based model to forecast growing season rainfall for Australian wheat belt. The 23rd International Congress on Modelling and Simulation (MODSIM), Canberra, Australia, 3-8 December 2019. (Extended Abstract, Accepted).

Contents

List of Figures

List of Tables

Glossary

APSIM	*Agricultural Production System sIMulator*
ARID	*Agricultural Reference Index for Drought*
BOM	*Bureau of Meteorology*
BRF	*bias-corrected random forest*
CDD	*consecutive dry days*
CDF	*cumulative distribution function*
CMIP5	*Coupled Model Intercomparison Project phase 5*
CV	*coefficient of variation*
ECEs	*extreme climate events*
ENSO	*El Niño Southern Oscillation*
GCM	*global climate models*
GEE	*Google Earth Engine*
GHG	*greenhouse gas*
IDW	*Inverse Distance Weighted*
IPCC	*Intergovernmental Panel on Climate Change*
LCCC	*Lin's concordance correlation coefficient*
MAE	*mean absolute prediction error*
MAPE	*Mean Absolute Percentage Error*
MLP	*multi-layer perceptron neural network*
MLR	*multiple linear regression*
MODIS	*Moderate Resolution Imaging Spectroradiometer*
mtry	*the number of randomly selected predictor variables at each node*
NDVI	*Normalized Difference Drought Index*
NSW	*New South Wales*
ntree	*the number of trees to grow in the forest*
PET	*potential evapotranspiration*
R^2	*coefficient of determination*
RCP	*Representative Concentration Pathway*
RF	*random forest*
RMSE	*root mean square error*
ROC	*receiver operating characteristic*
SA2	*Statistical Areas Level 2*
SILO	*Scientific Information for Land Owners*
SPEI	*Standardized Precipitation Evapotranspiration Index*
SPI	*Standardized precipitation index*
SVM	*support vector machine*
Tmax	*maximum land surface temperature*
Tmin	*minimum land surface temperature*
TRMM	*Tropical Rainfall Measuring Mission*
VIF	*variance inflation factor*

Abstract

Australian wheat production is crucial to global food security, as Australia is one of the world's major grain exporters. The NSW wheat belt is a main wheat production area in south-eastern Australia. Interannual wheat yields in the NSW wheat belt are highly variable, as the rainfed wheat cropping systems are significantly affected by recurrent climate and weather extremes. Ongoing climate change is projected to induce more extremes events, thereby leading to more unfavourable climate conditions for wheat production.

This thesis aims to quantify the impacts of various climate and weather extremes on wheat yield in the present and explore their potential impacts in the future, thereby enhancing the capability of stakeholders to reduce yield losses. Five inter-related studies based on statistical regression-based models, process-based crop models, or the integration of both models were conducted in the NSW wheatbelt. Consistent findings demonstrate that: (1) Inter-annual variability of rainfall in winter and spring was largely responsible for wheat yield variation. (2) Seasonal agricultural drought conditions could be well monitored for the wheat belt using remote sensing information and machine learning-based statistical models. (3) APSIM simulated biomass, multiple climate extremes indices, NDVI, and SPEI were incorporated into the RF model to develop a hybrid model for improved modelling of impacts of climate extremes. Drought events throughout the growing season were identified as the main factor causing yield losses. (4) The wheat belt was expected to experience drier conditions in spring and winter but had little change in summer and autumn. By the end of the 21st century, over half of the wheat belt was at a high risk of experiencing spring and winter drought. (5) The hybrid model was used to assess the impacts of future climate and weather extremes on wheat yield. Increasing drought and heat events around reproductive stages were identified to be major threats causing yield losses in the future.

This project enhanced systematic understanding of impacts of present and future climate and weather extremes on wheat yield and their likely changes in the future. However, certain aspects such as new crop cultivars, efficient management practices, pests and weed, were not explicitly considered in the modelling methods. Therefore, these findings should be further reconfirmed by models involving more influential information to guide agricultural production.

Key words: climate and weather extremes; climate change; wheat yield; machine learning; process-based crop models; Australia