EVALUATION OF NON-CHEMICAL WEED MANAGEMENT OPTIONS IN

ORGANIC RICE PRODUCTION

A Dissertation

by

SETH BERNARD ESTEBAN ABUGHO

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Muthukumar Bagavathiannan
Committee Members,	Xin-Gen Zhou
	Anna McClung
	Endang Septiningsih
Head of Department,	David Baltensperger

May 2020

Major Subject: Agronomy

ABSTRACT

Flooding, allelopathic varieties, and non-synthetic herbicides are potential options for weed management in organic rice production. However, little research has been conducted on the effectiveness of these tools for weed management in organic rice production under field conditions. Experiments were conducted from 2016 to 2018 to understand the impact of flooding on the emergence of five major weeds in rice, determine the weed suppressive potential of four potentially allelopathic rice varieties, and evaluate the efficacy of seven non-synthetic herbicides. All weeds but Palmer amaranth emerged at 2.5 cm flooding depth, though the degree of emergence varied across weed species. Weedy rice and barnyardgrass had <10% and <5% emergence, respectively, at 7.5 cm flooding depth. Flooding depth at 2.5 cm delayed the emergence of Amazon sprangletop, Nealley's sprangletop, barnyardgrass, and weedy rice by 8, 13, 8, and 2 days, respectively. With respect to weed suppressive rice varieties, PI 312777 was the best performing weed suppressive variety in the field with a relative yield of 60% and 81% in 2017 and 2018, respectively compared to a weed-free check. Among the non-synthetic herbicides evaluated, Homeplate® (caprylic acid + capric acid) showed good levels of weed control, causing 93% and 80% injury to broadleaf signalgrass and barnyardgrass, respectively. Rice injury with Homeplate® was substantial (46%) at 14 days after application (DAA), but rice crop recovered from this injury by 21 DAA. Overall, results from this research illustrate that these non-chemical options can be utilized as a part of an integrated weed management program in organic rice production.

DEDICATION

I dedicate this work to people who have meant so much to me:

First, to the rice farmers and producers worldwide, who took the challenges in producing organic rice. Thank you for your willingness and hard work to venture in this business.

Second, the rice researchers and agronomists who inspired me to be open-minded in adapting different aspects of weed control programs in rice. Your patience and diligence in research are necessary to technological advancements in rice production.

Third, I am dedicating this work to my Mom and Dad, Dinah and Bernardo, and my siblings, Mark, Cyrus, and Mary Ann for the unwavering support and love they gave me. My graduate school adventure would not have been complete without them. Mahal ko kayong lahat mula sa aking puso!

Finally, but not least, my sunshine that brightens my day while writing this dissertation, Breanna Nichole, no words can express how much I love you for all the support you gave me. You always “guac” my world! Te amo aking mahal!

ACKNOWLEDGEMENTS

I would like to thank my dissertation advisor, Dr. Muthukumar Bagavathiannan, for giving me the opportunity to work with him. He encouraged me to keep on moving forward towards scientific goals. His constant support, guidance and assistance inspired me to develop the skills and expertise necessary for a successful weed scientist. மிக்க நன்றி!

I also thank my graduate advisory committee members, Dr. Xin-Gen Zhou, Dr. Endang Septiningsih, and Dr. Anna McClung, for their guidance and support, contributing to the realization of this research.

I also thank Drs. Debalin Sarangi and Esther Shekinah for providing technical comments while writing my dissertation.

This work would not have been possible without the support from the staff at the David Wintermann Rice Research Station, Eagle Lake, Texas. I would like to express my appreciation to Mr. Jason Samford, Mr. Patrick Parma, Mr. John Korenek Jr., Mr. Henry Nieto, and Ms. Coleen Meitzen, for assisting with various aspects of my field research at the station. Special thanks also to Mr. Bryan Weise, organic rice farmer in the El Campo area, for allowing me to conduct an on-farm experiment in his fields.

I would like to express my appreciation to my Weed Science colleagues at Texas A&M University – Dr. Nithya Subramanian, Dr. Scott Nolte, Dr. Kathy Carson, Dr. Vijay Singh, Daniel Hathcoat, Shilpa Singh, Dr. Prabhu Govindasamy, Dr. Rui Liu, Aniruddha Maity, Swati Shreshta, Bishwa Sapkota, Spencer Samuelson, Blake Young, Cynthia Sias, Kathryn Sweeney, Chengsong Hu, Kaisa Werner, Rohith Vulchi, Zach Howard, Mason House, James Griffin, Bojana Pilipovic, and Zorika Vasic for the awesome memories. Long live the weeds!

Thanks as well to the faculty and staff at the Department of Soil and Crop Sciences, especially the Soil and Crops Graduate Organization for the camaraderie. It was an honor to work and study here!

Thanks also to my Brasileiro friends, Fabricia Reis, Bruno Giovanelli, Camila Grassmann, Queli Ruschel, Ana Pagenotto, Tamara Mundt, Paolo Ferreira, and Victor Cieza for teaching me and improving my Portuguese while working with me in the lab. Muito obrigado por tudo gente!

My BCS friends, Abishai, Joshua, Kyle, Sasha, Shun, Henry, Coley, Neil, Jessica, JP, and Eloy for the international camaraderie.

I also want to acknowledge Albert and Irene Flores and the Ibarra family for nurturing my Latin heritage. You've made my stay enjoyable while pursuing my graduate degree. I enjoyed the meals and company with y'all!

I express my thanks to the Filipino community in Houston, Texas, especially the Rodriguez, Bagui and Valeza families for making me feel at home always through delicious servings and baon of Filipino dishes.

Thanks also to my family in Vista, California, the Serna and Rivera families, for allowing me to be a part of your lives. Thank you for entrusting your beloved Bre to me.

Most important of all, my heartfelt appreciation to my family who were always behind me to support me even though they are miles away from me. Maraming salamat sa inyong walang sawang pagsuporta!

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Dr. Muthukumar Bagavathiannan (Chair), Dr. Xin-Gen Zhou, Dr. Anna McClung, and Dr. Endang Septiningsih. All other work conducted for the dissertation was completed by the graduate student independently.

Funding Sources

This research was funded by the USDA-NIFA Organic Agriculture Research and Extension Initiative (OREI) award # 2015-51300-24286.

The contents of this dissertation are solely the responsibility of the authors and do not necessarily represent the official views of the above organizations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

Under the United States Department of Agriculture (USDA) Organic Food Production Act (OFPA) Section 2109, "farmers engaging in organic agriculture shall not apply materials, engage in practices contrary to or inconsistent with, the applicable organic certification program" (USG 1990). Practices contrary to the organic certification program include the use of any fertilizers containing synthetic ingredients or any commercially blended fertilizers and application of synthetic herbicides as a method of weed control (USG 1990; Liebman et al. 2001). Organic certification is not granted to a producer using synthetic chemicals, including herbicides, to grow their crop. Increased adoption in organic farming systems is attributed to less fossil energy consumption, low soil erosion, high biodiversity interaction, reduced pesticide use and increased demand for organically-grown crops (Lockeretz et al. 1981; Arnhold et al. 2014; Fuller et al. 2005; Bond and Grundy 2001; Williams and Hammitt 2001). However, perceived challenges discourage some from pursuing organic farming. The exclusion of synthetic herbicide use complicates weed management in organic production systems and hampers the transition to organic crop production by conventional farmers (Decker et al. 2014; Bond and Grundy 2001). In fact, weed control is a serious problem in global crop production, whether conventional or organic (Rydberg and Milberg 2000; Owen et al. 2014). Although the demand for organic produce increased since the 1990s, improving weed control in organic production is a critical need (Thompson 1990). Organic systems have been mainly popular in vegetables and specialty legumes, but organic rice is an emerging industry. Application of innovative methods for weed control is key for promoting organic rice production.

Rice production in the midsouthern United States

Rice (*Oryza sativa* L.) is the most used cereal crop for direct human consumption worldwide (OECD-FAO 2018). In 2017, rice was the third most important cereal crop (production: 484 M metric tons) in the world after corn (*Zea mays* L.) (1,070 M metric tons) and wheat (*Triticum aestivum* L.) (755 M metric tons) (FAO 2018). Weeds are one of the major constraints to rice production and can potentially cause up to 35% yield loss (Oerke and Dehne 2004). Weed populations may vary depending on the type of crop planted, method of crop establishment, and the environment. Therefore, effective weed management strategies should be adopted based on the type of rice culture and location to avoid yield loss (Bennett et al. 2012; Bagavathiannan and Norsworthy 2012; Riar and Norsworthy 2011).

Direct-seeding and transplanting are two common rice establishment methods, and the direct-seeded system is the most popular in the Midsouthern United States (US) (Bond et al. 2007; Riar and Norsworthy 2011). Studies have reported that fields under dry-direct seeded rice had more weed infestations than the transplanted ones (Chauhan 2012; Chauhan et al. 2015). However, Rao et al. (2007) reported that weed infestation caused 20% yield loss in both rice production systems.

Majority of the problematic weed species infesting rice fields, including barnyardgrass (*Echinochloa crus-galli* [L.] P. Beauv.), rice flatsedge (*Cyperus iria* L.), yellow nutsedge (*Cyperus esculentus* L.), Amazon sprangletop (*Leptochloa panicoides*

[J. Presl.] Hitchc.), and weedy rice (*Oryza sativa* L.) belong to the Poaceae family. Barnyardgrass is one of the most problematic weeds in rice production fields in Midsouthern United States (Lovelace et al. 2002; Wilson et al. 2014; Zhang et al. 2005). In addition, the occurrence of herbicide resistance, especially to the acetolactate synthase (ALS)-inhibitors makes it a challenge for management in imidazolinone-tolerant (Clearfield®) rice, limiting available weed control tools (Bzour et al. 2017, Steele et al. 2002).

In addition to grass weeds, broadleaf weed species such as hemp sesbania (*Sesbania herbacea* [Mill.] McVaugh), eclipta (*Eclipta prostrata* L.) and purple ammannia (*Ammania robusta* Heer & Regel) also pose threat to rice production in Texas. Hemp sesbania has the ability to germinate from the deeper depths of soil and can grow in high moisture environments, favoring its emergence as one of the problematic broadleaf weeds in Midsouth rice (Bond et al. 2007; Johnston et al. 1979). The indiscriminate use of herbicides of same site of action in rice has led to the rapid evolution of herbicide-resistant weeds. For example, widespread occurrences of ALS inhibitor-resistant barnyardgrass in the Southern United States is a major problem for rice producers (Bagavathiannan et al.2014; Wilson et al. 2014) Therefore, integrated weed management approaches including cultural, mechanical, and chemical weed control are important for sustainability. Developing sustainable weed management programs in rice involve (1) understanding rice-weed competitive interactions, (2) developing integrated weed management methods, that include chemical and non-chemical tools, and (3) suppressing the evolution of weed adaptation in the system.

Chemical weed control

The use of herbicides is a major component of chemical weed control. Recommended herbicide programs for weed management in rice involve the application of a preemergence herbicide followed by postemergence applications. Propanil (photosystem II inhibitor) and fenoxaprop (Acetyl Coenzyme A Carboxylase inhibitor) are commonly used postemergence herbicides for controlling grass weed species in rice (Shaner 2014). Conversely, a combination of herbicides with cultural methods such as flooding lead to improved weed control in rice (Avila et al. 2005). In transplanted rice in Asia, pretilachlor (very long-chain fatty acid inhibitor) is a popular herbicide to control weeds (Nobuyoshi et al. 2002). Clomazone, quinclorac, thiobencarb, and pendimethalin are also commonly used preemergence herbicides in direct-seeded rice production in the US Midsouth (Lawrence et al. 2017; Jordan 1995; Noldin et al. 1999). However, the use of synthetic herbicides is prohibited in organic rice production; therefore, there is a need to test potential alternative weed management practices.

Use of non-synthetic chemicals

Several non-synthetic herbicides including vinegar and citric acid are used for the weed control in organic production systems. Vinegar (acetic acid), a non-selective contact herbicide, is used for weed control in several crops such as sweet corn, potato, and onion (Evans and Bellinder 2009). Previous research in Indonesia reported effective control of tropic ageratum (*Ageratum conyzoides*) and synedrella (*Synedrella nodiflora*) in medicinal plants using acetic acid (Rahayuningsih and Supriadi 2017). Citric acid is another non-synthetic chemical for weed control in organic crops. For example, Abouziena et al. (2009) reported that citric acid provided > 95% control of broadleaf weed species including strangler vine (*Morrenia odorata*), eastern black nightshade (*Solanum ptychanthum*) and velvetleaf (*Abutilon theophrasti*). Therefore, evaluating non-synthetic chemicals such as vinegar and citric acid for weed control in rice will be an important aspect. Additionally, there are several essential oils such as capric acid, caprylic acid, clove oil, etc. that were shown to have herbicidal properties; some of them are also commercially sold as non-synthetic herbicides. Evaluating them for weed control in organic rice production will be beneficial.

Non-chemical weed control

Cultural practices such as seeding method, integrating cover crops, and irrigation and nutrient management can be valuable for weed control in organic rice (Pannacci et al. 2017; Handiseni et al. 2015; Yamada et al. 2011; Yadav et al. 2014; Chauhan and Abugho 2013). However, limited information is available on organic crop production methods, especially on weed control, severely limiting the adoption of organic farming (Martinez-Eixarch et al. 2017). Some of the non-chemical tools that were tested in this research include flooding, allelopathic varieties, cover crops and the use of non-synthetic (plant-derived) herbicides.

Flooding. Flooding is an important component for weed control in rice (Bagavathiannan et al. 2011). It promotes an anoxic environment that leads to oxygen depletion, which in turn inhibits weed seed germination (Benvenuti and Macchia 1995). Manipulating flooding depth and the time of flooding initiation is necessary for effective weed control in rice (Kent and Johnson 2001). Moreover, understanding seedbank size and biology of weeds is necessary to implement flooding as an effective weed control tactic (Bagavathiannan et al. 2011; Kim et al. 2013). Different weed species may respond differently to flooding. The germination of several *Echinochloa* spp. was severely affected when flooding was introduced at early seedling phases (Chauhan 2012; Chauhan and Johnson 2011).

Allelopathy and crop competitiveness. Allelopathy can be considered a natural substitute for herbicides and can be an important component of integrated weed management (Singh et al. 2003). Allelopathy is a process involving the production of chemicals (called allelochemicals) from a plant, which can impact the growth and development of other plants (Rice 1984; Amb and Ahluwalia 2016). Several crops are known to produce allelochemicals. Cereal rye (*Secale cereale* L.) is a popular model crop for its allelopathic potential (Barnes and Putnam 1987); Schulz et al. (2013) recently summarized 16 compounds found in cereal rye seedlings that potentially impede with weeds. Grain sorghum (*Sorghum bicolor*) is another allelopathic crop that suppresses weed seed germination (Alsaadawi and Dayan 2009). Several rice accessions identified in the US have allelopathic activities on weeds including ducksalad and barnyardgrass (Dilday et al. 2001). Furthermore, rice varieties with allelopathic/weed suppressive potential were developed to provide additional weed control options (Gealy et al. 2013). PI312777, one of the weed suppressive varieties, caused 3 to 13% reduction in barnyardgrass biomass accumulation (Gealy et al. 2003). Gealy et al. (2005) reported that PI312777 produced more tillers and was aggressive against barnyardgrass. Huagan-3, another allelopathic rice variety bred using PI312777, inhibited root growth and altered the root morphology of *Cyperus difformis*, weedy rice, eclipta (*Eclipta prostrata*) and barnyardgrass (Yang and Kong 2017). Yang et al. (2017) also reported that Huagan 3 inhibited root growth of penoxsulam-resistant barnyardgrass.

In this study, we aim to develop a sustainable weed management program focusing on non-chemical options in organic rice production in Texas. The objectives of this research are to:

1. Understand the effect of flooding on the germination and growth of commonly found weed species in rice production in Texas
2. Evaluate the performance of rice varieties for weed suppression in an organic rice production system in Texas
3. Evaluate crop injury and weed control potential of non-synthetic herbicides applied to rice

The hypotheses underpinning the project objectives are:

1. Some weed species can germinate and establish better than others under flooded conditions in rice culture (Objective 1).
2. PI 312777 and PI 338046 rice varieties have weed suppressive potential compared to traditional cultivars, which can be used as an alternative weed management tool in organic rice system (Objective 2).
3. Non-synthetic herbicides can effectively control weeds in rice without causing high crop injury (Objective 3).

References

Abouziena HFH, Omar AAM, Sharma SD, Singh M (2009) Efficacy comparison of some new natural product herbicides for weed control at two growth stages. Weed Technol. 23:431-437

Adler MJ, Chase CA (2007) Comparison of the allelopathic potential of leguminous summer cover crops: Cowpea, sunn hemp, and velvetbean. Hort Sci. 42:289-293

Alsaadawi IS, Dayan FE (2009) Potentials and prospects of sorghum allelopathy in agroecosystems. Allelopathy J. 24: 255-270

Altieri MA, Lana MA, Bittencourt HV, Kieling AS, Comin JJ, Lovato PE (2011) Enhancing crop productivity via weed suppression in organic no-till cropping systems in Santa Catarina, Brazil. J. Sustain. Agric. 35:855-869

Amb MK, Ahluwalia AS (2016) Allelopathy: potential role to achieve new milestones in rice cultivation. Rice Sci. 23:165-183

Angaji SA, Septiningsih EM, Mackill DJ, Ismail AM (2010) QTLs associated with tolerance of flooding during germination in rice (*Oryza sativa* L.). Euphytica 172:159-168

Arnhold S, Lindner S, Lee B, Martin E, Kettering J, Nguyen TT, Koellner T, Ok YS, Huwe B (2014) Conventional and organic farming: Soil erosion and conservation potential for row crop cultivation. Geoderma 219: 89-105

Avila LA, Senseman SA, McCauley GN, Chandler JM, O'barr, GH (2005) Effect of flood timing on red rice (*Oryza* spp.) control with imazethapyr applied at different dry-seeded rice growth stages. Weed Technol. 19:476-480

Bagavathiannan MV, Norsworthy JK (2012) Late-season seed production in arable weed communities: management implications. Weed Sci. 60:325-334

Bagavathiannan MV, Norsworthy JK, Scott RC (2011) Comparison of weed management programs for furrow-irrigated and flooded hybrid rice production in Arkansas. Weed Technol. 25:556-562

Bagavathiannan MV, Norsworthy JK, Smith KL, Burgos N (2011) Seedbank size and emergence pattern of barnyardgrass (*Echinochloa crus-galli*) in Arkansas. Weed Sci. 59:359-365

Bagavathiannan MV, Norsworthy JK, Smith KL, Neve P (2014) Modeling the simultaneous evolution of resistance to ALS- and ACCase-inhibiting herbicides in barnyardgrass (*Echinochloa crus-galli*) in Clearfield rice. Weed Technol. 28:89-103

Barnes JP, Putnam AR (1987) Role of Benzoxazinones in allelopathy by rye (*Secale cereale* L.). J. Chem. Ecol. 13:889-906

Benevenuti S, Macchia M (1995) Effect of hypoxia on buried weed seed germination. Weed Res. 35:343-351

BennettAJ, BendingGD, ChandlerD, Hilton S, Mills P (2012) Meeting the demand for crop production: the challenge of yield decline in crops grown in short rotations. Biol. Rev. 87:52-71

Bernstein ER, Stoltenberg DE, Posner DE, Hedtcke JL (2014) Weed community dynamics and suppression in tilled and no-tillage transitional organic winter rye-soybean systems. Weed Sci. 62:125-137

Bond JA, Walker TW, Webster EP, Buehring NW, Harrell DL (2007) Rice cultivar response to penoxsulam. Weed Technol. 21:961-965

Bond W, Grundy AC (2001) Non-chemical weed management in organic farming systems. Weed Research 41: 383-405

Buchanan AL, Kolb LN, Hooks CR (2016) Can winter cover crops influence weed density and diversity in a reduced tillage vegetable system? Crop Prot. 90:9-16

Bzour MI (2017) Introduction of imidazolinone herbicide and Clearfiled rice between weedy rice-control efficiency and environmental concerns. Environ. Rev. 26. 181-198

Chauhan BS (2012) Weed ecology and weed management strategies for dry-seeded rice in Asia. Weed Technol. 26:1-13

Chauhan BS, Abugho SB (2013) Effects of water regime, nitrogen fertilization, and rice plant density on growth and reproduction of lowland weed *Echinochloa crus-galli*. Crop Prot. 54:142-147

Chauhan BS, Awan TH, Abugho SB, Evangelista G, Yadav S (2015) Effect of crop establishment methods and weed control treatments on weed management, and rice yield. Field Crops Res. 172:72-84

Chauhan BS, Johnson DE (2011) Ecological studies on *Echinochloa crus-galli* and the implications for weed management in direct-seeded rice. Crop Prot. 11:1385-1391

Chinery D (2002) Using acetic acid (vinegar) as a broad-spectrum herbicide. Available at http://ccerensselaer.org/resources/using-acetic-acid-vinegar-as-a-broad-spectrum-herbicide. Accessed April 6, 2018

Chun-huo Z, Zun-kang Z, Xiao-hua P, Shan H, Xue-ming T, Jian-fu W, Qing-hua S (2016) Integration of growing milk vetch in winter and reducing nitrogen fertilizer application can improve rice yield in double-rice cropping system. Rice Sci. 23:132-143

Couëdel A, Alletto L, Tribouillois H, Justes É (2018) Cover crop crucifer-legume mixtures provide effective nitrate catch crop and nitrogen green manure ecosystem services. Agric. Ecosys. Environ. 254:50-59

DeDecker JJ, Masiunas JB, Davis AS, Flint CG (2014) Weed management practice selection among Midwest US organic growers. Weed Sci. 62:520-531

Dilday RH, Mattice JD, Moldenhauer KA, Yan W (2001) Allelopathic potential in rice germplasm against ducksalad, redstem and barnyard grass. J. Crop Prod. 2:287-301

Evans GJ, Bellinder RR (2009) The potential use of vinegar and a clove oil herbicide for weed control in sweet corn, potato, and onion. Weed Technol. 23:120-128

Food and Agriculture Organization (2018) Worldwide production of grain in 2016-17, by type (in million metric tons). In Statista-The Statistics Portal. Retrieved

February 8, 2018, from https://www.statista.com/statistics/263977/world-grain-production-type/

Fuller RJ, Norton LR, Feber RE, Johnson PJ, Chamberlain DE, Joys AC, Mathews F, Stuart RC, Townsend MC, Wolfe MS, Macdonald DW, Firbank LG (2005) Benefits of organic farming to biodiversity vary among taxa. Biology Lett. 1:431-434

Gealy DR, Estorninos Jr. LE, Gbur EE, Chavez RS (2005) Interference interactions of two rice cultivars and their F_3 cross with barnyardgrass (*Echinochloa crus-galli*) in a replacement series study. Weed Sci. 53:323-330

Gealy DR, Wailes EJ, Estorninos Jr LE, Chavez RSC (2003) Rice cultivar differences in suppression of barnyardgrass (*Echinochloa crus-galli*) and economics of reduced propanil rates. Weed Sci. 51:601-609

Gealy D, Moldenhauer K, Duke S (2013) Root distribution and potential interactions between allelopathic rice, sprangletop (*Leptochloa* spp.), and barnyardgrass (*Echinochloa crus-galli*) based on 13C isotope discrimination analysis. J. Chemic. Ecol. 39:186-203

Gianessi LP, Reigner NP (2007) The value of herbicides in US crop production. Weed Technol. 21:559-566

Golden BR, Lawrence BH, Bond JA, Edwards HM, Walker TW (2017) Clomazone and starter nitrogen fertilizer effects on growth and yield of hybrid and inbred rice cultivars. Weed Technol. 31:207-216

Handiseni M, Jo YK, Zhou XG (2015) Integration of Brassica cover crop with host resistance and azoxystrobin for management of rice sheath blight. Plant Disease 99:883-885

Hole DG, Perkins AJ, Wilson JD, Alexander IH, Grice PV, Evans AD (2005) Does organic farming benefit biodiversity? Biol. Conserv. 122:113-130

Ibañez C, Curco A, Riera X, Ripoll R, Sanchez C (2010) Influence on birds of rice field management practices during the growing season: a review and an experiment. Waterbirds 33:167–180

Jabran K, Mahajan G, Sardana V, Chauhan BS (2015) Allelopathy for weed control in agricultural systems. Crop Prot. 72:57-65

Johnston SK, Walker RH, Murray DS (1979) Germination and emergence of hemp sesbania (*Sesbania exaltata*). Weed Sci. 27:290-293

Jordan D (1995) Efficacy of reduced rates of quinclorac applied with propanil or propanil plus molinate in dry0seeded rice (*Oryza sativa*). Weed Technol. 45:824-828

Kent R, Johnson DE, Becker M (2001) The influences of cropping system on weed communities of rice in Côte d’Ivoire, West Africa. Agric. Ecosyst. Environ. 87:299-307

Kent RJ, Johnson DE (2001) Influence of flood depth and duration on growth of lowland rice weeds, Cote d’Ivoire. Crop Prot. 20:691-694

Kim DH, Kim HT, Kim JG (2013) Effects of water level and soil type on the survival and growth of *Persicaria thunbergii* during early growth stages. Ecol. Eng. 61:90-93

Kim SY, Gutierrez J, Kim PJ (2012) Considering winter cover crop selection as green manure to control methane emission during rice cultivation in paddy soil. Agric. Ecosys. Environ. 161:130-136

Kumar V, Ladha JK (2011) Direct seeding of rice: recent developments and future research needs. In Adv. Agron. (Vol. 111:297-413) Academic Press

Lee CH, Do K, Park KY, Jung MA, Ali D, Lee, Gutierrez J, Kim PJ (2010) Effect of Chinese milk vetch (*Astragalus sinicus* L.) as a green manure on rice productivity and methane emission in paddy soil. Agric. Ecosys. Environ. 138:343-347

Liebman M, Davis AS, Francis C (2009) Managing weeds in organic farming systems: an ecological approach. Organic farming: the ecological system. Agron. Mono. 54: 173-195

Liebman M, Mohler Cl, Staver CP (2001) Ecological management of agricultural weeds. Cambridge University Press

Lockeretz W, Shearer G, Kohl DH (1981). Organic farming in the corn belt. Science 211: 540-547

Lovelace M, Talbert RE, Skulman BW, Scherder EF (2002) Evaluation of physiological responses in quinclorac-resistant and -susceptible barnyardgrass. Proc. South. Weed Sci. Soc. 55:114

Martínez-Eixarch M, Curcó A, Ibáñez C (2017) Effects of agri-environmental and organic rice farming on yield and macrophyte community in Mediterranean paddy fields. Paddy Water Environ. 3:457-468

McCouch SR, Zhao K, Wright M, Tung CW, Ebana K, Thomson M, Reynolds A, Wang D, DeClerck G, Ali ML, McClung A (2010) Development of genome-wide SNP assays for rice. Breeding Sci. 60:524-535

Miro B, Longkumer T, Entila FD, Kohli A, Ismail AM (2017) Rice seed germination underwater: morpho-physiological responses and the bases of differential expression of alcoholic fermentation enzymes. Frontiers Plant Sci. 8:1857

Miyauchi N, Kobayashi K, Usui K (2002) Differential safening activity of dymron and fenclorim on pretilachlor injury in rice seedlings in soil. Weed Biol. Mgt. 2:46-51

Muzell Trezzi M, Vidal RA, Balbinot Jr AA, von Hertwig H, Bittencourt JP, da Silva Souza Filho AP (2016) Allelopathy: driving mechanisms governing its activity in agriculture. J. Plant Interact. 11:53-60

Noldin JA, Chandler JM, Ketchersid ML, McCauley GN (1999) Red rice (*Oryza sativa*) biology. II. Ecotype sensitivity to herbicides. Weed Technol. 13:19-24

Norsworthy JK, McClelland M, Griffith G, Bangarwa SK, Still J (2011) Evaluation of cereal and Brassicaceae cover crops in conservation-tillage, enhanced, glyphosate-resistant cotton. Weed Technol. 25:6-13

Norsworthy JK. Bond J, Scott RC (2013) Weed management practices and needs in Arkansas and Mississippi rice. Weed Technol. 27:623-630

Oerke EC (2006) Crop losses to pests. J. Agric. Sci. 144:31-43

Oerke EC, Dehne HW (2004) Safeguarding production-losses in major crops and the role of crop protection. Crop Prot. 23:275-285

Organization for Economic Co-operation and Development – Food and Agriculture Organization (2018) The Agriculture Outlook 2018 to 2027. http://www.agri-outlook.org/Agricultural-Outlook-2018.pdf Accessed October 30, 2018

Owen MD, Beckie HJ, Leeson JY, Norsworthy JK, Steckel LE (2015) Integrated pest management and weed management in the United States and Canada. Pest Manag. Sci. 71:357-376

Pannacci E, Lattanzi B, Tei F (2017) Non-chemical weed management strategies in minor crops: a review. Crop Prot. 96:44-58

Rahayuningsih S, Supriadi S (2014) Herbicidal efficacy of acetic acid and citric acid base on broad leaf weeds of medicinal crop fields. Bul. Littro. 25:137-143

Rao AN, Johnson DE, Sivaprasad B, Ladha JK, Mortimer AM (2007) Weed management in direct-seeded rice. Adv. Agron. 93:153-255

Reis AFDB, de Almeida REM, Chagas Jr AF, Nascente AS (2017) Effect of cover crops on soil attributes, plant nutrition, and irrigated tropical rice yield. Rev. Caatinga. 30:837-846

Riar DS, Norsworthy JK (2011) Use of imazosulfuron in herbicide programs for drill-seeded rice (*Oryza sativa*) in the mid-South United States. Weed Technol. 25:548-555

Rice EL (1984) Allelopathy, 2nd edition. Rice EL, editor. Orlando: Academic Press; p. 422

Roth RT, Ruffatti MD, O'Rourke PD, Armstrong SD (2018) A cost analysis approach to valuing cover crop environmental and nitrogen cycling benefits: A central Illinois on farm case study. Agric. Sys. 159:69-77

Rydberg NT, Milberg P (2000) A survey of weeds in organic farming in Sweden. Biological Agric. Horti. 18:175-185

Schulz M, Marocco A, Tabaglio V, Macias FA, Molinillo JM (2013) Benzoxazinoids in rye allelopathy-from discovery to application in sustainable weed control and organic farming. J. Chemic. Ecol. 39:154-174

Shaner DL (2014) Herbicide handbook. Weed Science Society of America. IL: Champaign, p.191

Singh, HP, Batish DR, Kohli RK (2003) Allelopathic interactions and allelochemicals: new possibilities for sustainable weed management. Crit. Rev. Plant Sci. 22:239-311

Smith RJ (1988) Weed thresholds in southern US rice, *Oryza sativa*. Weed Technol. 2:232-241

Smith-Fiola D (2014) Vinegar: an alternative to glyphosate. https://extension.umd.edu//sites/extension.umd.edu/files/_docs/programs/ipmnet/Vinegar-AnAlternativeToGlyphosate-UMD-Smith-Fiola-and-Gill.pdf.Accessed: April 6, 2018

Steele G, Chandler J, McCauley G (2002) Control of red rice (*Oryza sativa*) in imidazolinone-tolerant rice (*O. sativa*). Weed Technol. 16:627-630

Thompson GD (1998) Consumer demand for organic foods: what we know and what we need to know. American Journal of Agricultural Economics 80:1113-1118

United States Government (1990) Organic Foods Production Act. Available at: https://www.ams.usda.gov/sites/default/files/media/Organic%20Foods%20Production%20Act%20of%201990%20(OFPA).pdf. Accessed: May 6, 2019

Williams PR, Hammitt JK (2001) Perceived risks of conventional and organic produce: pesticides, pathogens, and natural toxins. Risk Analysis 21:319-330

Wilson MJ, Norsworthy JK, Scott RC, Gbur EE (2014) Program approaches to control herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in midsouthern United States rice. Weed Technol. 28:39–46

Yadav S, Evangelista G, Faronilo J, Humphreys E, Henry A, Fernandez L (2014) Establishment method effects on crop performance and water productivity of irrigated rice in tropics. Field Crops Res. 166:112-127

Yamada S, Kusumoto Y, Tokuoka Y, Yamamoto S (2011) Landform type and land improvement intensity affect floristic composition in rice paddy fields from central Japan. Weed Res. 51:51-62

Yang XF, Kong CH (2017) Interference of allelopathic rice with paddy weeds at the root level. Plant Biol. 19:584-591

Yang XF, Kong CH, Yang X, Li YF (2017) Interference of allelopathic rice with penoxsulam-resistant barnyardgrass. Pest Manag. Sci. 73:2310-2317

Zhang W, Webster EP, Blouin DC, Leon CT (2005) Fenoxaprop interactions for barnyardgrass (*Echinochloa crus-galli*) control in rice. Weed Technol. 19: 293-297

CHAPTER II

IMPACT OF FLOODING ON THE EMERGENCE AND GROWTH OF RICE WEEDS

Introduction

Rice (*Oryza sativa* L.) is one of the most consumed cereals in the world and serves as an important source of energy for humans (Muthayya et al. 2014; Awika 2011). Although the vast majority of rice is cultivated in Asia, rice has been widely grown in the Americas (Marchesi and Chauhan 2019; Espe et al. 2016). In the United States, an average of 8.6 Metric tons ha^{-1} of rice was harvested in 2018 (USDA ERS 2019). The major conventional rice producing states in the US consists of Arkansas, California, Mississippi, Missouri, Louisiana and Texas (USA Rice 2019). In the United States, organic rice production is considered a specialty crop and contributed $42.7 M value to the total rice production in the country; Texas, the leading organic rice producer, contributed $13.7 M in 2016 (USDA 2017). Both conventional and organic rice is produced to cater to the needs of rice consumers in the US.

Weed management is critical both in conventional and organic rice production (Barberi 2001; Teasdale et al. 1991; Derksen et al. 1993). Weeds compete with rice for critical resources such as nutrients, photosynthetic radiation, and moisture, severely reducing yields and often leading to total crop loss depending on the severity of infestation (Okafor and De Datta 1976; Smith Jr. 1968; Keeley and Thullen 1978). In rice, weeds cause yield loss potential up to 37% if not managed properly (Oerke 2006).

In Texas, several grass and broadleaf weed species infest rice production systems. Liu (2018) conducted a survey of problematic weed species in Texas rice production to help rice farmers address appropriate weed control measures. These weed species include barnyardgrass (*Echinochloa crus-galli*), junglerice [*Echinochloa colona* (L.) Link], yellow nutsedge (*Cyperus esculentus* L.) hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh] and weedy rice (*Oryza sativa* L.) (Liu 2018).

Barnyardgrass, a C4 weed species, is a problematic grass species in rice having evolved resistance to multiple herbicide sites of actions such as acetyl CoA carboxylase synthase and acetolactate synthase (Bagavathiannan et al. 2012; Heap 2019). Barnyardgrass left uncontrolled can cause 2000 to 4000 kg ha^{-1} reductions in rice yield (Mitich 1990). Stauber et al. (1991) found that barnyardgrass at a density of 60 plants m^{-2} can reduce the rice grain and straw yield by 2000 kg ha^{-1} and 4000 kg ha^{-1}, respectively in comparison with a weed-free control. Furthermore, Bagavathiannan et al. (2014) created a model assumption that rice monocropping and frequent use of herbicides with single site-of-action often results in failure to control barnyardgrass in the US Midsouth region. Therefore, barnyardgrass is the most troublesome weed in rice.

Weedy rice, oftentimes referred to as red rice, is another problematic weed of rice (Delouche et al 2007; Chauhan 2012). In Arkansas, the leading rice producing state in the US, a survey reports weedy rice infested 60% of the fields allotted for rice production (Burgos et al. 2008). The morphological and physical similarities between cultivated and weedy rice made weedy rice control difficult. Thus, the presence of weedy rice reduces the grain quality of rice thereby requiring more flood water use to reduce red rice emergence (Delouche et al. 2007; Sanders and Jordan 1999). Similarly, Amazon sprangletop (*Leptochloa panicoides*) and Nealley's sprangletop (*Leptochloa nealleyi*) are most frequently encountered weeds in rice production systems in Louisiana and Texas, and they can thrive well under the wet environments of a rice field (Baskin et al. 1999; Bergeron et al. 2015).

Hemp sesbania, a leguminous weed species found in the Midsouth US rice production systems, can compete with rice through shading and can potentially cause significant rice yield reduction (Street and Mueller 1993). As a matter of fact, hemp sesbania was ranked in the top ten most problematic rice weed species in survey conducted by Norsworthy et al. (2013.). Another unlikely weed in rice in Texas is Palmer amaranth (*Amaranthus palmeri*), a dioecious species belonging to the Amaranth family (Ward et al. 2013). Palmer amaranth can become problematic weed during the early rice stages prior to flood establishment similar to slender amaranth (*Amaranthus viridis* L.) and spiny amaranth (*Amaranthus spinosus* L.) in a direct-seeded rice system (Chauhan and Johnson 2009). Palmer amaranth can compete with rice is due to its rapid growth rate adding to the weed's reputation as a noxious weed in different cropping systems in the US (Jha and Norsworthy 2009; Ward et al. 2013). Palmer amaranth ranks fifth problematic rice weed in the Arkansas and Mississippi rice growers survey (Norsworthy et al. 2013). Thus, Palmer amaranth became an important weed in rice due to the soybean-rice rotation system, a common practice in the US midsouthern crop production (Wilson 2010).

Organic farming creates a positive impact to the environmental such as reduced herbicide dependency in agriculture to control weeds (Reganold and Wachter 2016). The long-term environmental benefits of organic farming such as biodiversity, improved soil health and fertility, enhanced soil nutrient cycling, and increased microbial activity are well-documented (Bonanomi et al. 2016; Birkhofer et al. 2008; Reganold et al. 1987 Krebs et al. 1999; Rigby and Caceres 2001). In the early 2000s, significant movements toward beneficial tariff and trade on organic crops increased awareness towards organic food production worldwide (Raynolds 2000). This resulted to a substantial production of organic crops adding a considerable share in the world market due to an increasing demand in organic food, especially cereal crops such as rice (IFOAM 2016).

Organic rice producers in the US adhere to the core practices mandated by the United States Department of Agriculture (USDA) in terms of pest management. The USDA considers one of the core practices of organic farming involves "use of biological control, crop rotations, and other techniques to manage weeds, insects and diseases" (USDA-SARE 2006). Mulching, biological, thermal, and mechanical weed control are some of the weed management tools frequently used by the organic growers in the US (Bond and Grundy 2001). However, weed management in organic system is challenging (Liebman and Davis 2009). Losses to weeds in organic rice system may be even higher compared to conventional rice if not addressed with appropriate tools (Gealy et al. 2012; Kong et al. 2008). Using effective and timely weed management tools such as flood manipulation and the use of allelopathic varieties are keys to making organic rice a more profitable and acceptable produce in the market (Kent and Johnson 2001; Gealy et al. 2012).

Flood is a well-known cultural weed control in rice production (Kaya-Altop et al. 2019). Flooding changes soil physical and chemical characteristics affecting the germination and emergence of weeds. Reactive oxygen species, low O_2 solubility, and presence of chemical radicals cause poor seed germination in flooded soils (Voesenek et al. 2006; Smith Jr and Fox 1973). Flooding combined with other management practices can be used as an effective strategy for controlling weeds in rice (Kent and Johnson 2001). However, limited information is available on the impact of flooding on emergence and growth of the commonly found rice weeds in Texas. In addition, little is known in most aquatic species with respect to flooding and its interaction with light and/ temperature (Baskin and Baskin 1998). Nevertheless, flooding reduces weed seed germination (Pons 1982). The objectives of this research were to 1) evaluate the impact of flooding depths on the emergence of six weed species (Amazon sprangletop, barnyardgrass, hemp sesbania, Nealley's sprangletop, Palmer amaranth, weedy rice) and 2) assess the growth and development of these species in response to flooding treatments initiated at different growth stages of weeds. We hypothesized that deeper flooding depth and prolonged continuous flood duration would negatively impact the emergence and growth weed species tested in this study.

Materials and methods

Plant materials. Six most frequently encountered rice weed species in Texas including Amazon sprangletop, barnyardgrass, hemp sesbania, Nealley's sprangletop, Palmer amaranth, weedy rice were used in this study. All weed seeds (except Amazon sprangletop and Palmer amaranth) were collected in June 2016 from a rice field near Eagle Lake, TX (29.35°N, -96.20°W). Amazon sprangletop and Palmer amaranth were obtained in June 2016 from Azlin Seed® (Azlin Seed Service, 112 Lilac Dr, Leland, Mississippi, USA azlin-seed-service.hub.biz). Seeds were stored dry at 4 C prior to the study.

Germination tests were conducted to check the seed vigor prior to the greenhouse experiments. Fifteen seeds of each species were placed in 9 cm diameter Petri dishes containing Whatman No. 1 filter paper and 10 mL of distilled water was added to each Petri dish. Two Petri dishes per weed species were prepared and placed in an incubator at day/night temperatures of 30/20 C (12/12 hours). The radicle protrusion at 7 days were recorded for documenting their germination.

Impact of flooding on weed emergence. Experiments were conducted in 2016 and 2017 at the Norman Borlaug Center in Texas A&M University, College Station, Texas, to evaluate the impact of flooding on germination of weeds. The experimental design was a two-factor randomized complete block with four replications. Three levels of flood depths [Periodic irrigation (flushed), 2.5 cm flood depth and 7.5 cm flood depth] were included in this study. The 2.5 cm depth was used to simulate shallow flooding during the initial rice stages and the 7.5 cm depth was used to simulate the local farmer practice. Water level was monitored on a daily basis to maintain a constant flood depth during the entire study. Plastic containers of 35 x 21 x 12 cm in length, height and width, respectively, were used. Pots for the periodic irrigation treatment was drilled to make holes for water drainage. A 1:1 ratio of field soil (sand: silt: clay 59%:24%:17%) and potting mix (Sungro®, www.sungro.com) was used for this study. 250 seeds each of the study species were planted in each container. Emerged seedlings were counted and removed once every four days for a month.

Impact of flooding on weed growth and development. A greenhouse study was conducted at the Norman Borlaug Center at Texas A&M University to assess the impact of flooding to plant height, aboveground and belowground biomass accumulation. The treatments were laid out in a randomized complete block design with eight replications. Two flooding depths: 0 (flush irrigated) and 10 cm (flooded), were introduced at four different weed growth stages[<0.5 (just emerged), 1, 2, 5 and 10 cm height]. Five seeds of the species used were planted in to a Styrofoam cup (17 cm tall × 15 cm dia) filled with soil mix described earlier. All pots with flood treatments were placed in large storage containers (L×W×H:50 cm×41 cm× 32 cm) to achieve the deep flooding condition. Weed seedling survival was recorded per species. Leaf area data for all weeds but hemp sesbania and Palmer amaranth were recorded at harvest using Licor 3100 leaf area meter since broadleaf weed species were not able to survive the flood treatments. Plant height, aboveground and belowground biomass data were recorded at physiological maturity for all the weed species but Palmer amaranth since the species did not survive flooding.

Statistical analysis. All laboratory and greenhouse experiments. Cumulative emergence data were converted into the percentage of cumulative emergence relative to the periodic flush treatment (control), and data were subjected to ANOVA using JMP 13.0 (JMP Pro, SAS Institute Inc. Cary, NC). Cumulative emergence data were regressed over the d after planting using a three-parameter sigmoid model in SigmaPlot 13.0 (Systat Software Inc., San Jose, CA):

$$Y = a/\ (1+\exp^{-[(X-X_0)/b)}] \qquad [1]$$

where Y is the cumulative seedling emergence (%) at X (days after planting); a is the maximum seedling emergence (%), X_0 is the time (d) to reach 50% of maximum seedling emergence, and b is the slope of the sigmoidal function. Parameter estimates of the model was compared using two-tailed *t*-tests (P ≤ 0.05). The goodness-of-fit parameters such as root mean square error (RMSE) and model efficiency coefficient (Ef) were calculated using the equations (Sarangi et al. 2016):

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{1/2} \qquad [2]$$

$$E_f = 1 - [\![\sum_{i-1} n(O_i - P_i)\,/\,\sum_{i=1} n(O_i - \overline{O}_i)^2]\!] \qquad [3]$$

Data for plant height, leaf area aboveground and belowground biomass relative to the flushed-irrigated check were combined for analysis and subjected to ANOVA using JMP 13.0 (JMP Pro, SAS Institute Inc. Cary, NC).

Results and discussion

Germination tests. All weed seeds used in this study had 100% germination (Data not shown). The broadleaf weed species, hemp sesbania in particular, had the very good seed germination.

Impact of flooding on emergence of weed species. Year-by-flooding depth interactions were not significant. Data from the repeated experiments were combined as there were no significant interaction effects of treatments and experiments.

Thus, data were pooled over two runs. Flood depth and weed species was significant. All the weed species emerged at 2.5 cm flooding depth except for Palmer amaranth (Figure 1). In a field experiment conducted in hybrid rice in Arkansas, Bagavathiannan et al. (2011) observed that Palmer amaranth emergence was low or none under flooded conditions. The inability of Palmer amaranth to tolerate flood conditions offers rice producers focus to control flood tolerant species in rice. Hemp sesbania, another broadleaf weed species tested in this study, showed minimal (5%) emergence at 2.5 cm flooding depth. Hemp sesbania has the ability to germinate under flooded conditions but prolonged imbibition affects the emergence of hemp sesbania under water (Williams 1980). In contrary to the broadleaf weed species, weedy rice, barnyardgrass, and Amazon sprangletop in 2.5 cm flooding depth had 38%, 20% and 17% emergence, respectively (Figure 1). Weedy rice, which has similar morphological characteristics with cultivated rice, was expected to emerge from the shallow flooding depth (e.g., 2.5 cm) (Delouche et al. 2007). However, emergence of weedy rice was greatly impacted (<10% emergence) by the higher flooding depth (7.5 cm) (Figure 1) Previous studies reported about the reduced seed germination of weedy rice when seeds were placed in a deeper soil depth along with a flooding treatment (Smith Jr and Fox 1973). Therefore, deep flooding can be used as a non-chemical tool for weedy rice control in rice. At 7.5 cm flood depth, barnyardgrass emergence was <5% (Figure 1). Smith and Fox (1973) reported that no barnyardgrass emergence was observed when flooding depth was 5.1 cm regardless the seeding depth in the soil. The low emergence of barnyardgrass at 7.5 cm flooding depth can be attributed to the low oxygen levels present in the soil under submerged or flooded conditions (Arai and Matsunaka 1966; Bonnewell et al. 1982). In addition to reduced oxygen levels in the soil, light and temperature can play a role in the emergence of *Leptochloa* spp. Seeds require light and optimum temperature (20-30 degrees C) for germination (Khan and Gulzar 2003). The daytime greenhouse temperature where the study was conducted can reach up to 35 degrees C. Baskin et al. (1999) reported reduced emergence of *Leptochloa* spp. under flooded condition with temperature ranges from 30 to 35 degrees C. Optimum germination in *Leptochloa* spp. ranges at a constant lower temperature (25/15 degrees C) (Baskin et al. 1999). The germination percentage of the *Leptochloa* spp. in our study may have been affected through the combined temperature and reduced oxygen levels. Baskin and Baskin (1998) also reports that germination of aquatic species can be influenced by water temperature. Flooding depth by weed species interaction was significant for both years. Flood depth at 2.5 cm delayed the emergence of Amazon sprangletop, Nealley's sprangletop, barnyardgrass, and weedy rice by 8, 13, 8, 2 days, respectively (Figure 2). At 2.5 cm flooding depth, weedy rice took only 4 d to reach to the 50% of the cumulative emergence, whereas it was $\geq$ 8 d for other weeds (Table 1). Therefore, it is evident that the higher adaptability of weedy rice to flooded situation favored this weed to become problematic in rice production in Texas. Thus, pregerminated rice seeds can be used to field with weedy rice infestation if the grower plans to use organic method. Weed seed decay of problematic weed species, such as weedy rice, is enhanced as a result of deeper flood levels, especially if the rice seed has already a radicle (Smith Jr 1985). Flooding depth at 7.5 cm delayed the emergence of weed species compared to the 2.5 cm depth and the 50% of cumulative emergence was obtained at 12, 12, and 10 d after planting for barnyardgrass, weedy rice, and hemp sesbania, respectively. It is assumed that the limited supply of oxygen in 7.5 cm flooding depth caused the delay in weed emergence (Rumpho and Kennedy 1981). Rice seeds under submerged conditions have a mean germination time of 3 d (Huang et al. 2019). Therefore, growers are advised to adjust their weed management practices with the changing flooding depths in rice during the critical period of rice seed emergence. Our results imply that delayed weed seed emergence offer the crop to gain competitive advantage as they transition to the canopy closure stage (Gibson et al. 2002).

Impact of flooding on weed seedling survival. Palmer amaranth did not survive regardless of the height when flood was introduced (Figure 3). The Leptochloa species survived 75 to 94% when flood was introduced at 5 and 10 cm. Weedy rice had 94 to 100% survival when flood was introduced at 1 to 10 cm. However, when flood was introduced at less than 1 cm, weedy rice had 68% emergence. Due to similar morphological characteristics to rice, weedy rice can survive and emerge flooded conditions. Our results were similar to Chamara et al. (2018) that rice can have 69.6% emergence when flooded at 2 cm depth. Therefore, we can control weedy rice using flood if introduced while the seeds are still emerging.

Impact of flooding on weed growth and development. Flood introduced at earlier growth stages of weeds impacted the aboveground biomass (Figure 4). Aboveground and belowground biomass were relative to the flushed treatments. Palmer amaranth, due to its inability to withstand flood, had negligible aboveground and belowground biomass. Palmer amaranth, a terrestrial weed species, ceases all physiological and morphological function such as root development under continuous flooding condition ultimately affecting the weed growth (Norsworthy et al. 2011). Hemp sesbania, another broadleaf weed in rice, produced only 9% aboveground biomass if flood is introduced at $\leq$ 2 cm (Figure 4). Conversely, the belowground biomass relative to the flushed-irrigated check of hemp sesbania was 479 and 419% when flood was initiated at 5 and 10 cm height, respectively (Figure 5). It is evident that the increase in belowground biomass in hemp sesbania at the later stage- flooding treatments was due to the aerenchymatous cell production in plant roots (personal observation; Figure 6). Thus, hemp sesbania control is not attainable using flood if the weed is above 5 cm in height allowing increased competition with the crop due to extensive root adaptation to flood.

Most of the grass species used in this study accumulated aboveground and belowground biomass relative to the flushed-irrigated check. Barnyardgrass and weedy rice produced >90% aboveground biomass relative to the flush-irrigated treatment when flooded at 5 cm height (Figure 4). Weedy rice was able to survive the flooding treatments introduced at all the growth stages, whereas barnyardgrass had 91 to 105% aboveground biomass when flooded at 5 and 10 cm height (Figure 4). In this study, both relative aboveground and belowground biomass production was low in barnyardgrass and weedy rice if flood is introduced at an early growth stage ($\leq$2 cm). The findings in lower biomass production flooded at the early growth of barnyargdgrass in this study agrees with the previous research done by Chauhan and Johnson (2011) that flooding reduces biomass production up to 57% if introduced immediately after sowing of rice. Although the flood depth in this study is 10 cm, the biomass accumulation of weedy rice in our study is in agreement with previous research that weedy rice biomass production could be reduced up to 87% at 2 cm flood depth (Chauhan 2012). Flood introduced at $\leq$ 2 cm height of Amazon sprangletop and Nealley's sprangletop resulted to 0% biomass produced relative to the flushed treatment. Furthermore, the sprangletop species only accumulated 112 to 135% belowground biomass relative to the flushed-irrigated check when flooded at 5 and 10 cm depth (Figure 5). Understanding the response of the aboveground and belowground biomass production helps to identify the significance of flooding in rice. Flooding promotes the accumulation of CO_2 in the roots and reduces the available O_2 resulting to senescence of most plant species (Smith and Fox 1973). Relative leaf area was recorded for barnyardgrass and weedy rice (Figure 7). Barnyardgrass flooded either at 5 cm or 10 cm had 97.41 to 100.46 % leaf area relative to the flushed-irrigated check while weedy rice leaf area ranged from 87.51 to 92.82%. Regardless of flood treatment, once barnyardgrass and weedy rice emerge of the flood level, these grass species compensate in leaf production. The results in this study aligns with the research of Gibson and Fisher (2001) that *Echinochloa* and *Oryza* species can produce leaf area of 1940 mm2 and 848 mm^2 leaf area under full sunlight. No plant height data was collected for Palmer amaranth since the weed did not survive the flood treatments (Table 2). Most grass species had similar relative height compared to the flush-irrigated check other than Nealley's sprangletop. When flooded at 5 cm height Nealley's sprangletop had 58% relative plant height.

Practical implications

Overall, the current study highlights the different response of weed species using flood as a tool in rice production, organic rice in particular. Flood-tolerant weed species such as weedy rice, barnyardgrass, and hemp sesbania pose potential risks to organic rice producers. Therefore, understanding the morphology and biology of weed species should be reviewed and understood especially, in the advent of climate change while implementing effective water management to reduce problematic weed species in rice (Harker and O' Donovan 2013; Smith Jr and Fox (1973). In Texas, where the majority of organic rice is produced, flooding provides a valuable tool for weed control. However, a single approach to control weeds, such as flood management, in an organic rice production system is not sufficient (Norsworthy et al. 2012). Thus, the inclusion of other cultural weed control practices such as the use of allelopathic varieties, cover crops, and non-synthetic herbicides needs to be evaluated in establishing a good weed control program, in addition to flooding, in an organic rice system.

References

Arai M, Matsunaka S (1966) Control of barnyardgrass in paddy fields in Japan. Japanese Agric. Res. Quar. 1:5-9

Awika JM (2011) Major cereal grains production and use around the world In Awika JM, Piironen V, and Bean S (Eds.) Advances in Cereal Science: implications to food processing and health promotion. American Chemical Society New Jersey: Atlantic City

Badgley C, Moghtader J, Quintero E, Zakem E, Jahi Chappeli M, Aviles-Casquez K, Samulon A, Perfecto I (2007) Organic agriculture and the global food supply. Renew Agri Food Syst 22:86-108

Bagavathiannan MV, Norsworthy JK, Smith KL, Neve P (2012) Seed production of barnyardgrass (*Echinochloa crus-galli*) in response to time of emergence in cotton and rice. J Agrl. Sci. 150:717-724

Bagavathiannan MV, Norsworthy JK, Scott RC (2011). Comparison of weed management programs for furrow-irrigated and flooded hybrid rice production in Arkansas. Weed Technol. 25:556-562

Bagavathiannan MV, Norsworthy JK, Smith KL, Neve P (2014) Modeling the simultaneous evolution of resistance to ALS-and ACCase-inhibiting herbicides in barnyardgrass (*Echinochloa crus-galli*) in Clearfield® rice. Weed Technol. 28:89-103

Bàrberi P (2002) Weed management in organic agriculture: are we addressing the right issues? Weed Res. 42:177-193

Baskin CC, Baskin JM, Chester EW (1999) Seed germination ecology of the annual grass *Leptochloa panicea* ssp. *mucronata* and a comparison with *L. panicoides* and *L. fusca*. Acta Oecol. 20:571-577

Baskin JM, Baskin CC (1988) Role of temperature in regulating the timing of germination in *Portulaca oleracea*. Can J. Bot. 66:563-567

Bergeron EA, Webster EP, McKnight BM, Rustom SY Jr (2015) Evaluation of herbicides for Nealley's sprangletop (*Leptochloa nealleyi*) control. http://www.cbai2015.com.br/docs/trab-2-6875-365.pdf. Accessed: April 25, 2019

Birkhofer K, Martijn Bezemer T, Bloem J, Bonkowksi M, Christensen S, Dubois D, Ekelund F, Flierbach A, Gunst L, Hedlund K, Mader P, Mikola J, Robin C, Setala H, Tatin-Froux F, Van der Putten WH, Scheu S (2008) Long-term organic farming fosters below and aboveground biota: implications for soil quality, biological control and productivity. Soil Biol. Biochem. 40:2297-2308

Bonanomi G, De Filippis F, Cesarano G, La Storia A, Ercolini D, Scala F (2016) Organic farming induces changes in soil mircrobiota that affect agro-ecosystem functions. Soil Biol. Biochem. 103:327-336

Bond W, Grundy AC (2001) Non-chemical weed management in organic farming systems. Weed Res. 41:383-405

Bonnewell V, Koukkari WL, Pratt DC (1983) Light, oxygen, and temperature requirements for *Typha latifolia* seed germination. Can. J. Bot. 61:1330-1336

Bridges DC (1995) Ecology of weeds. Pages 19-34 in Smith AE, ed. Handbook of weed management systems. New York: Marcel Dekker, Inc.

Burgos NR, Norsworthy JK, Scott RC, Smith KL (2008) Red rice (*Oryza sativa*) status after 5 years of imidazolinone-resistant rice technology in Arkansas. Weed Technol. 22: 200-208

Chamara BS, Marambe B, Kumar V, Ismail AM, Septiningsih EM, Chauhan BS (2018) Optimizing sowing and flooding depth for aerobic germination-tolerant genotypes to enhance crop establishment, early growth, and weed management in dry-seeded rice (*Oryza sativa* L.) Front Pl. Sci. 9:1-14

Chauhan BS (2012) Weed ecology and weed management strategies for dry-seeded rice in Asia. Weed Technol. 26:1-13

Chauhan BS (2012) Weedy rice (*Oryza sativa*) II. Response of weedy rice to seed burial and flooding depth. Weed Sci. 60: 385-388

Chauhan BS, Johnson DE (2009) Germination ecology of spiny (*Amaranthus spinosus*) and slender (*A. viridis*): troublesome weeds of direct-seeded rice. Weed Sci. 57: 379-385

Chauhan BS, Johnson DE (2011) Ecological studies on *Echinochloa crus-galli* and the implications for weed management in direct-seeded rice. Crop Prot. 30: 1385-1391

Delmotte S, Tittonell P, Mouret JC, Hammond R, Lopez-Ridaura S (2011) On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate. Europ. J. Agron. 35:223-226

Delouche JC, Burgos NR, Gealy DR de San Martin GZ, Labrada R, Larinde M, Rosell, C (2007) Weedy Rices-Origin, Biology, Ecology, and Control. FAO Plant Production and Protection Paper 188, FAO, Rome, Italy

Derksen DA, Lafond GP, Thomas AG, Loeppky HA, Swanton CJ (1993) Impact of agronomic practices on weed communities: tillage systems. Weed Sci. 41:409-417

Espe MB, Cassman KG, Yang H, Guilpart N, Grassini P, Van Wart J, Anders M, Beighley D, Harrell D, Linscombe S, McKenzie K, Mutters R, Wilson LT, Linquist BA (2016) Yield gap analysis of US rice production systems shows opportunities for improvement. Field Crops Res. 196:276-283

Gibson KD, Fischer AJ, Foin TC, Hill JE (2002) Implications of delayed *Echinochloa* spp. germination and duration of competition for integrated weed management in water- seeded rice. Weed Res. 42:351-358

Harker KN, O'Donovan JT (2013) Recent weed control, weed management, and integrated weed management. Weed Technol 27:1-11

Heap I (2019). The international Survey of Herbicide Resistant Weeds. Online resource at http:www.weedscience.org. Accessed April 24, 2019

Huang YC, Yeh TH, Yang CY (2019) Ethylene signaling involves in seeds germination upon submergence and antioxidant response elicited confers submergence tolerance to rice seedlings. Rice. 12:23. DOI: http://doi.org/10.1186s12284-019-0284-z

IFOAM (2016) The world of organic agriculture: statistics and emerging trends. Accessed March 22, 2018. http://orgprints.org/31151/1/willer-lernoud-2016-world-of-organic.pdf

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci. 57:644-651

Kaya-Altop E, Şahin M, Jabran K, Phillippo CJ, Zandstra BH, Mennan H (2019) Effect of different water management strategies on competitive ability of semi-dwarf rice cultivars with *Echinochloa oryzoides*. Crop Prot. 116:33-42

Khan MA, Gulzar S (2003) Light, salinity, and temperature effects on the seed germination of perennial grasses. Ameri. J. Bot. 90:131-134

Keeley PE, Thullen RJ (1978) Light requirements of yellow nutsedge (*Cyperus esculentus*) and light interception by crops. Weed Sci. 26:10-16

Kent RJ, Johnson DE (2001) Influence of flood depth and duration on growth of lowland rice weeds, Cote d'Ivoire. Crop Prot. 20:691-694

Krebs JR, Wilson JD, Bradbury RB, Siriwardena GM (1999) The second silent spring? Nature. 400:611-612

Liebman M, Davis AS, Francis C (2009) Managing weeds in organic farming systems: an ecological approach. Organic farming: the ecological system. Agron. Monogr. 54:173-195.

Liu, Rui (2018). Survey, Ecology and Management of Problematic Weeds in Rice Production in Texas. Doctoral dissertation, Texas A & M University. Available electronically from http://hdl.handle.net/1969.1/174367

Londo JP, Schaal BA (2007) Origins and population genetics of weedy red rice in the USA. Mol. Ecol. 16:4523-4535

Lundkvist A, Salomonsson L, Karlsson L, Gustavsson AMD (2008) Effects of organic farming on weed flora composition in a long term perspective. Europ. J. Agron. 28:570-578

Marchesi C, Chauhan BS (2019) The efficacy of chemical options to control *Echinochloa crus-galli* in dry-seeded rice under alternative irrigation management and field layout. Crop Prot.118: 72-78

Mitich LW (1990) Intriguing world of weeds: barnyardgrass. Weed Technol. 4:918-920

Muthayya S, Sugimoto JD, Montgomery S, Maberly GF (2014) An overview of global rice production, supply, trade, and consumption. Ann. NY Acad. Sci. 1324:7-14

Norsworthy JK, Bond J, Scott RC (2013) Weed management practices and needs in Arkansas and Mississippi rice. Weed Technol. 27:623-630

Norsworthy JK, Scott RC, Bangarwa SK, Griffith GM, Wilson MJ, McClelland M (2011) Weed management in a furrow-irrigated imidazolinone resistant hybrid rice production system. Weed Technol. 25:25-29

Norsworthy JK, Scott RC, Bangarwa SK, Griffith GM, Wilson MJ, McClelland M (2011) Weed management in a furrow-irrigated imidazolinone-resistant hybrid rice production system. Weed Technol. 25:25-29

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci. 60:31-62

Oerke EC (2006) Crop losses to pests. J. Agric. Sci. 144:31-43

Okafor LI, De Datta SK (1976) Competition between upland rice and purple nutsedge for nitrogen, moisture, and light. Weed Sci. 24:43-46

Pons TL (1982) Factors affecting weed seed germination and seedling growth in lowland rice in Indonesia. Weed Res. 22:155-161

Raynolds L (2000) Re-embedding global agriculture: The international organic and fair trade movements. Agric. Human Val. 17:297-309

Reganold JP, Elliott LF, Unger YL (1987) Long-term effects of organic and conventional farming on soil erosion. Nature 330:370-372

Reganold JP, Wachter JM (2016) Organic agriculture in the twenty-first century. Nature Plants 2: 1-8

Rigby D, Cáceres D (2001) Organic farming and the sustainability of agricultural systems. Agric. Sys. 68:21-40

Rumpho ME, Kennedy RA (1981) Anaerobic metabolism in germinating seeds of *Echinochloa crus-galli* (barnyard grass): Metabolite and enzyme studies. Plant Physiol. 68:165-168.

Sanders DE, Jordan D (1999) Pest management. Louisiana Rice Production Handbook. LSU Agri Ctr Publ. 2321. Baton Rouge: LA. PP 37-50

Seufert V, Ramankutty N, Foley JA (2012) Comparing the yields of organic and conventional agriculture. Nature 485:229-231

Smith Jr RJ (1985) Control of red rice (*Oryza sativa*) in water-seeded rice (*O. sativa*). Weed Sci. 29:663-666

Smith Jr RJ, Fox WT (1973) Soil water and growth of rice and weeds. Weed Sci. 21:61-63

Smith RJ (1968) Weed competition in rice. Weed Sci. 16:252-255

Stauber LG, Smith Jr RJ, Talbert RE (1991) Density and spatial interference of barnyardgrass (*Echinochloa crus-galli*) with rice (*Oryza sativa*). Weed Sci. 39:163-168

Street JE, Mueller TC (1993) Rice (*Oryza sativa*) weed control with soil applications of quinclorac. Weed Technol. 7:600-604

Teasdale JR, Beste CE, Potts WE (1991) Response of weeds to tillage and cover crop residue. Weed Sci. 39:195-199

United States Department of Agriculture, Economic Research Service (2019) https://www.ers.usda.gov/data-products/rice-yearbook/.Accessed: October 16, 2019)

USA Rice (2019) https://www.thinkrice.com/on-the-farm/where-is-rice-grown/. Accessed: October 16, 2019

USDA-SARE (2006) What are organic production and practices? https://www.nal.usda.gov/afsic/organic-productionorganic-food-information-access- tools#systems. Accessed: March 28, 2018

Voesenek LACJ, Colmer TD, Pierik R, Millenaar FF, Peeters AJM (2006) How plants cope with complete submergence. New Phytol. 170:213-226

Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): a review. Weed Technol. 27:12-27

Williams RD (1980) Moisture stress and hydration-dehydration effects on hemp sesbania (*Sesbania exaltata*) seed germination. Weed Sci. 28:487-492

Wilson CE, Runsick Jr Sk, Mazzanti R (2010) Trends in Arkansas rice production. In BR Wells Rice Research Studies 2009. Arkansas Agricultural Experiment Station Res Ser 581: 11-21

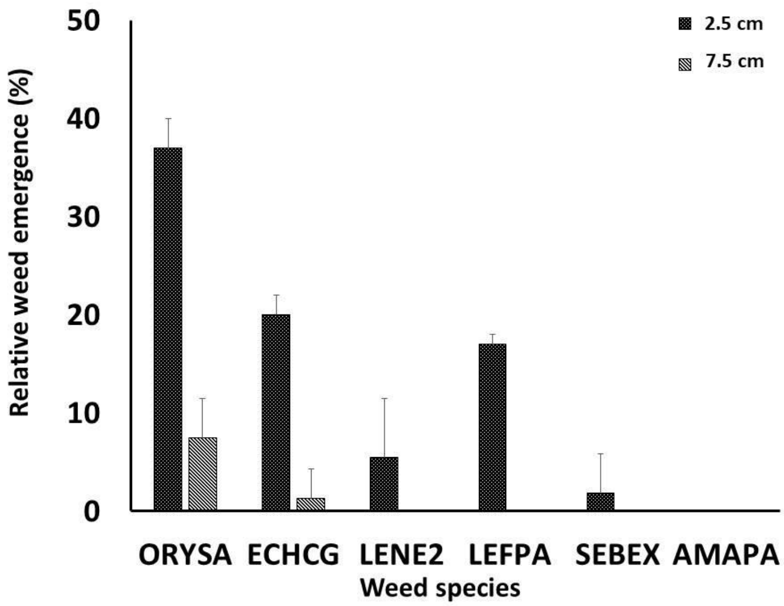


Figure 1. Emergence percentage (relative to the periodic flush flooding treatment) of six weed species as influenced by different depth of flooding.
*Weed species codes retrieved from the Weed Science Society of America (WSSA) composite list of weeds. AMAPA: *Amaranthus palmeri* (Palmer amaranth); ECHCG: *Echinochloa crus-galli* (barnyardgrass); LENE2: *Leptochloa nealleyi* (Nealley's sprangletop); LEFPA: *Leptochloa panicoides* (Amazon sprangletop); ORYSA: *Orysa sativa* (weedy rice); SEBEX: *Sesbania herbacea* (hemp sesbania)

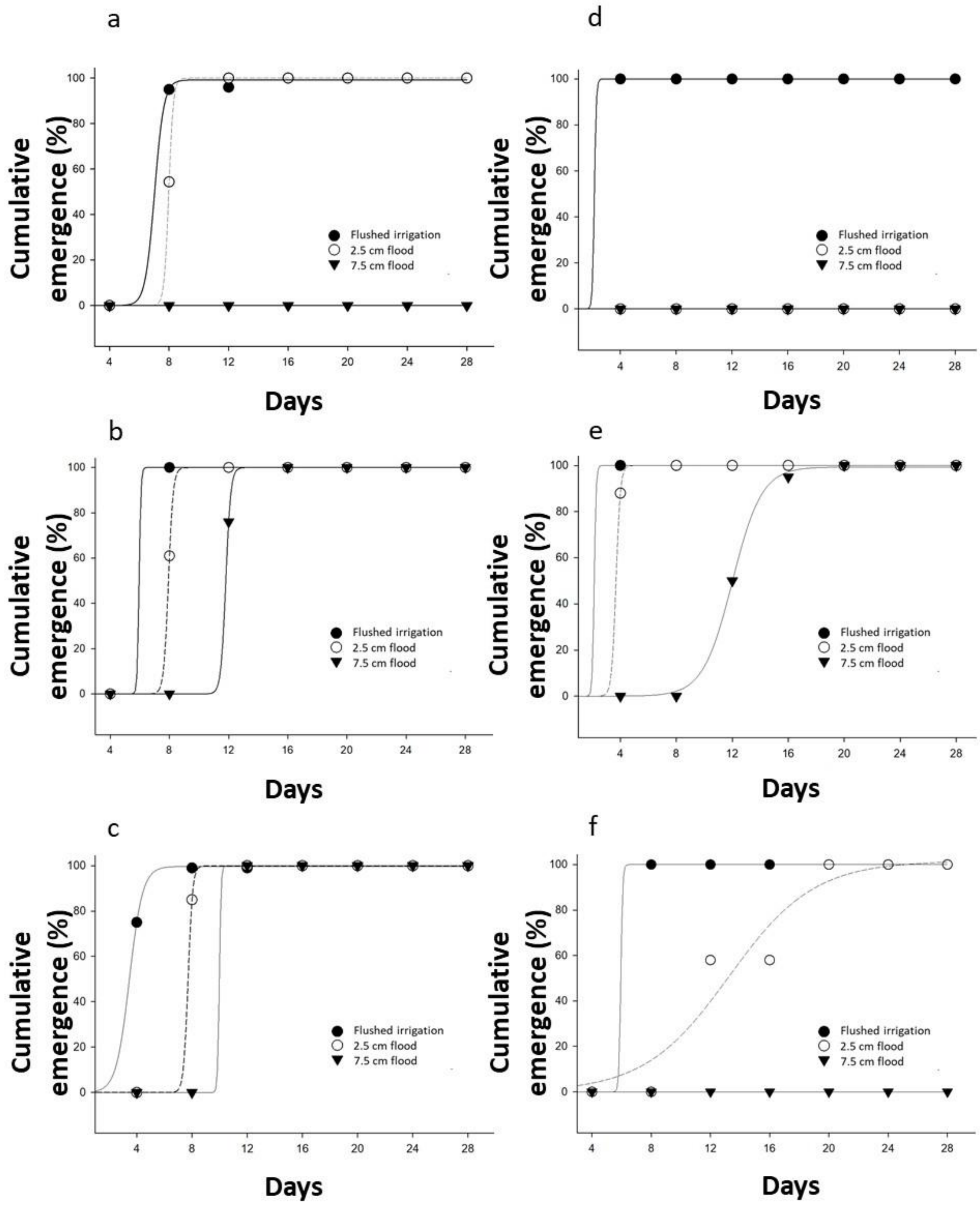


Figure 2. Seedling recruitment pattern of a) Amazon sprangletop, b) barnyardgrass, c) hemp sesbania, d) Palmer amaranth, e) weedy rice, and f) Nealley's sprangletop as influenced by flooding depth

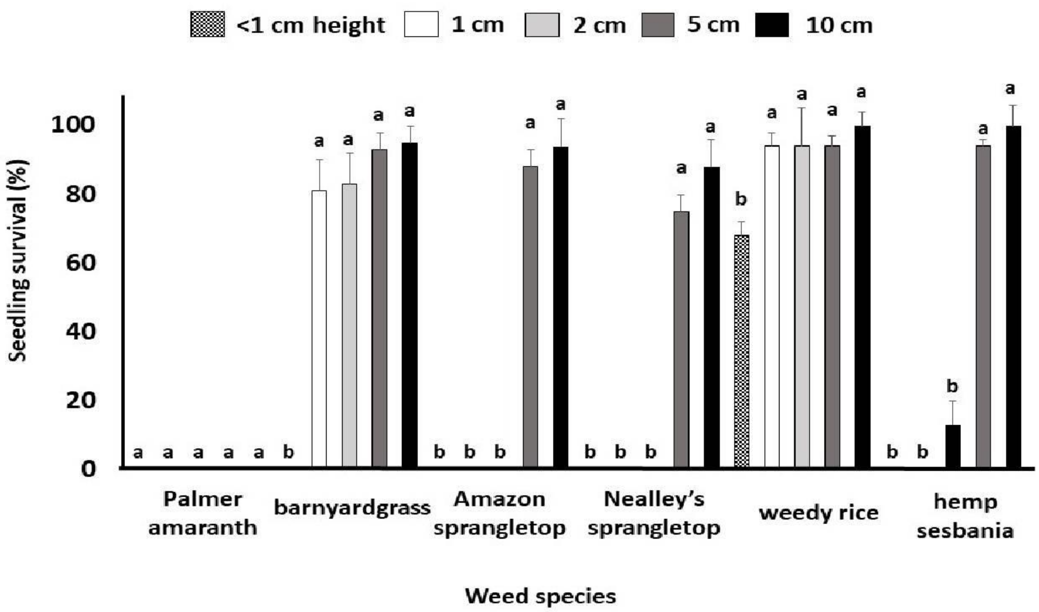


Figure 3. Impact of flooding to seedling survival of six weed species

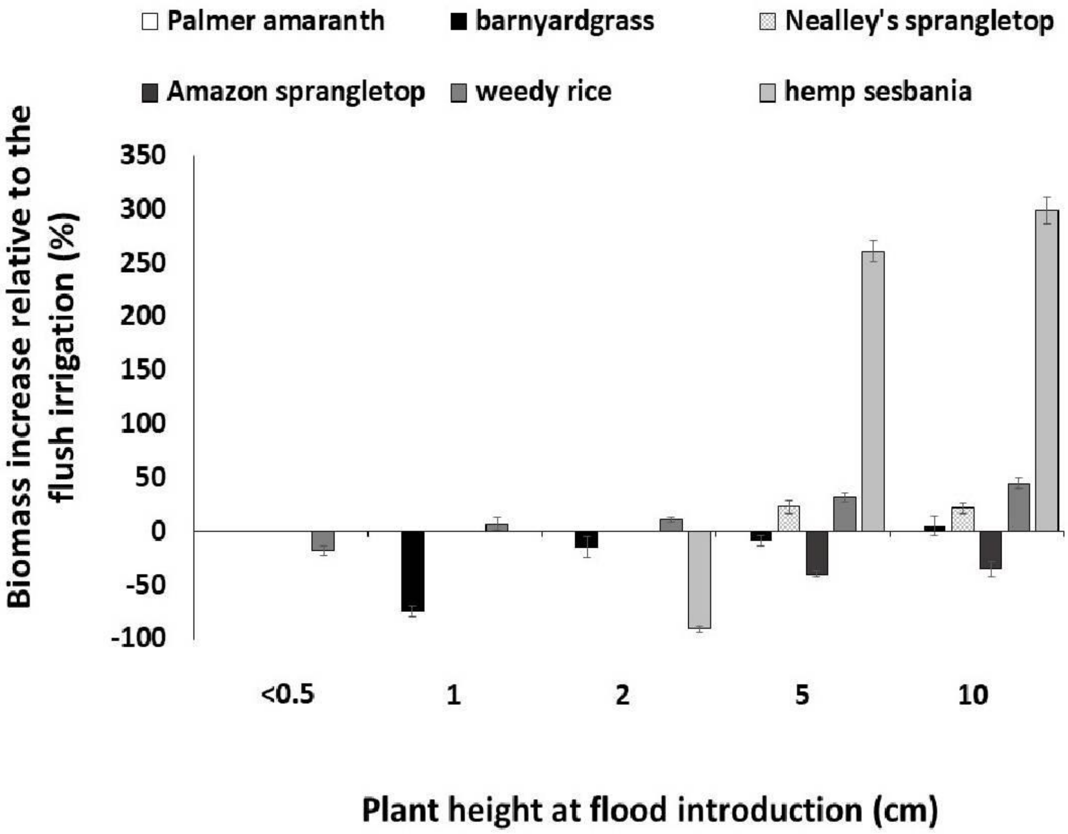


Figure 4. Impact of flooding to aboveground biomass of six weed species relative to flushed irrigation treatments.

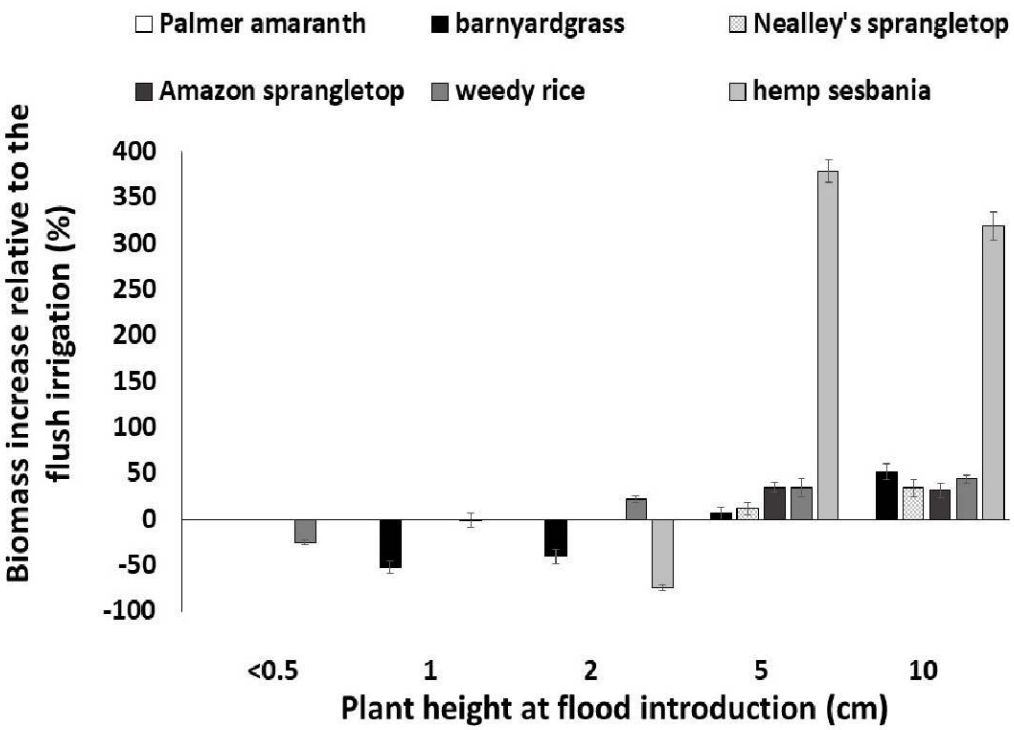


Figure 5. Impact of flooding to belowground biomass of six weed species relative to flushed irrigation treatments.

Figure 6. Aerenchyma formation of hemp sesbania roots flooded at 10 cm height.

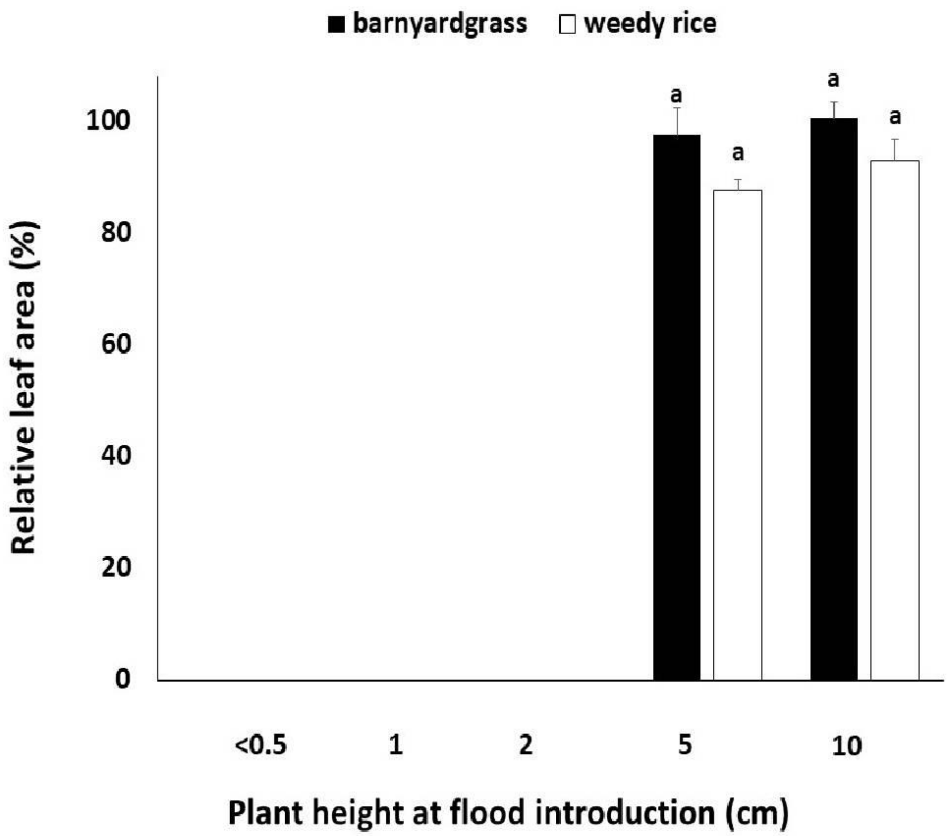


Figure 7. Impact of flooding to leaf area of surviving species (barnyardgrass and weedy rice) relative to flushed irrigation treatments.

Table 1. Estimates of the sigmoidal parameters and model goodness of fit of the emergence of six weed species conducted at the Norman Borlaug Center, Texas A&M University

Weed species[a]	**Flooding depth**	**Parameter estimate**[b]		**Model goodness of fit**[c]	
	cm	**b**	**X_0**	**RMSE**	**E_f**
AMAPA	**0**	0.07	2	5.28	0.99
	2.5	-[d]	-	-	-
	7.5	-	-	-	-
ECHCG	**0**	0.06	6	4.36	0.99
	2.5	0.16	8	3.84	0.99
	7.5	0.17	12	3.10	0.99
LENE2	**0**	0.06	6	3.40	0.99
	2.5	2.86	13	3.90	0.99
	7.5	-	-	-	-
LEFPA	**0**	0.31	7	5.16	0.99
	2.5	0.15	8	3.90	0.99
	7.5	-	-	-	-
ORYSA	**0**	0.07	2	3.40	0.99
	2.5	0.16	4	3.94	0.99
	7.5	1.05	12	5.44	0.99
SEBEX	**0**	0.48	3	4.88	0.99
	2.5	0.16	8	3.45	0.99
	7.5	0.06	10	2.61	0.99

[a]Weed species codes retrieved from the Weed Science Society of America (WSSA) composite list of weeds. AMAPA: *Amaranthus palmeri*; ECHCG: *Echinochloa crus-galli*; LENE2: *Leptochloa nealleyi*; LEFPA: *Leptochloa panicoides*; ORYSA: *Oryza sativa*; SEBEX: *Sesbania herbacea*.
[b]Values obtained from fitted three-parameter sigmoid curve using the equation: $Y = a/ [1+\exp^{-[(X-X_0)/b)}]$ explain the parameters and their units; where, Y is the cumulative seedling emergence (%) at X (days after planting); a is the maximum seedling emergence (100%), X_0 is the time (d) to reach 50% of maximum seedling emergence, and b is the slope of the sigmoidal function. Parameter estimates of the model was compared using two-tailed *t*-tests ($P \leq 0.05$).
[c]Abbreviations: E_f, model efficiency coefficient; RMSE, root mean square error.
[d]-Plant did not survive, Thus, no data was recorded.

Table 2. Impact of flooding to plant height of six weed species relative to flushed irrigation treatments[a]

Weed height[b]	**Weed species[cd]**					
	AMAPA	**ECHCG**	**LENE2**	**LEFPA**	**ORYSA**	**SEBEX**
cm	----------------------	----------------------	----------------------	%----------------------	----------------------	----------------------
<0.5	-	-	-	-	-	-
1	-	82 a	-	-	82 b	-
2	-	80 a	-	-	90 ab	13 b
5	-	91 a	58 b	90 a	102 a	69 a
10	-	103 a	100 a	93 a	103 a	73 a
p-values	-	0.2330	0.0007	0.3450	0.0551	<0.0001

[a]Plant height was collected at physiological maturity of the weed species.

[b]Weed height was measured when the flooding treatments were initiated.

[c]Weed species codes retrieved from the Weed Science Society of America (WSSA) composite list of weeds. AMAPA: *Amaranthus palmeri*; ECHCG: *Echinochloa crus-galli*; LENE2: *Leptochloa nealleyi*; LEFPA: *Leptochloa panicoides*; ORYSA: *Oryza sativa*; SEBEX: *Sesbania herbacea*.

[d]Means followed by the same letter in a column are not significantly different at $P<0.05$. Means were separated using Fisher's protected LSD ($\alpha=0.05$).

CHAPTER III

EVALUATION OF WEED SUPPRESSIVE RICE VARIETIES AS A MANAGEMENT TOOL IN ORGANIC RICE PRODUCTION

Introduction

Rice (*Oryza sativa* L.) is one of the most consumed grain crops of the world, cultivated either conventionally or organically (Mir and Bosco 2014). Most rice in the United States is under conventional cultivation in the mid-southern states of Arkansas, Louisiana, Mississippi and Texas. The USDA (2019) data shows that rice was grown in an area of 1,027,901 ha with a total production of 9.5 M metric tons in the US (2019). Weeds are a major production problem and are continuous constraint in most rice production systems; in particular, weeds such as water paspalum (*Paspalum modestum* [Mez]), rice flatsedge (*Cyperus iria* L.), hemp sesbania (*Sesbania herbacea* [Mill.] McVaugh) and barnyardgrass (*Echinochloa crus-galli* [L.] P. Beauv.) (Bagavathiannan et al. 2011; Brabham et al. 2019; Osterholt et al. 2019; Telo et al. 2019). Use of herbicides is one of the most effective and efficient tools of weed control in a conventional rice production system (Norsworthy et al. 2019). Nevertheless, excessive use of herbicides in controlling weeds increases the negative impact on the environment (Reganold and Wachter 2016) and in development of herbicide resistant weeds. Therefore, shifting to organic rice production is beneficial since it provides long-term environmental benefits including improved soil health, enhanced soil microbial activity (Bonanomi et al. 2016) and a premium price.

Organic rice production in the US, as documented from the late 20^{th} century, has seen a continuous rise over the years (USDA-NASS 2017). The current area under organic rice in the United States is 12,913 ha with a production of 1.4 M metric tons, Texas holding the top spot with a production of 63,562 metric tons in 2016 (USDA-NASS 2017). However, organic rice production has been challenging and increases in production can only be realized through improved varieties and better agronomic cultivation practices, effective weed control being one of them (Chauhan et al. 2015; Norsworthy et al. 2019). In an organic system, the options for weed control are very limited. Problematic weed species in rice production can become dominant in organic systems, especially if it can tolerate flooding, since flooding is considered an important and viable tool in controlling weeds (Kent and Johnson 2001). Most research on organic weed management are reported on vegetable and fruit crops such as carrot (*Daucus carota* ssp. *sativus*), pepper (*Capsicum annuum*), watermelon (*Citrullus lanatus*), and celery (*Apium graveolens*) (Baumann et al. 2001; Franco et al. 2018; Isik et al. 2009; Peruzzi et al. 2007). Mulching and cover cropping are some of the other commonly adopted weed control practices in organic vegetable production (Campanelli et al. 2019; Gheshm and Brown 2018). Unfortunately, these tools of organic vegetable and fruit production are not readily transferable to rice due to differences in the rice establishment and production methods including flooding. Tillage can be another option to control weeds but is again dependent on existing soil conditions (Liebman et al. 2004). Currently, pre-plant cultivation, flooding and hand weeding are the available options for weed control in organic rice cultivation (Mendoza 2004). Flooding in an organic rice field is a critical management practice for weed control (Kent and Johnson 2001). As a flood tolerant crop, rice can compete with weeds if flooding is done early in the season right after planting (Xu et al. 2013). In France, mechanical weeding in an organic rice production was done by passing a tractor-drawn cultivator between rice rows (Mouret et al. 2004). However, with just flooding and mechanical weed control as options, weed infestation has become the primary constraint in achieving the desired organic rice yield. As in conventional production, having additional tools that are effective for weed control is the need (Delmotte et al. 2011). In this scenario, weed suppressive varieties offer this diversity as a tool for weed control.

Rice varieties with allelopathy/weed suppressive potential help address weed problems in rice. However, quantifying allelochemicals and their stability in the soil environment can be challenging unless targeted experiments in the field or greenhouse are conducted with a specific design (Falquet et al. 2014; Cheng 1992). Most commercial varieties adapted to organic rice production systems of the mid-southern US do not have weed suppressive characteristics, and the use of allelopathic rice varieties depends on the preference of the rice grower. Nevertheless, allelopathic and weed suppressive rice varieties can be viable tools for weed control in organic rice production. A popular allelopathic variety worthy of introduction is PI 312777 (Gealy et al. 2003). This variety derived through crossing the T65*2 and TN1 rice lines was developed at the International Rice Research Institute in Philippines (Gealy et al. 2005; GRIN 2019). It requires sufficient moisture throughout the cropping season to achieve desired yield (Barnaby et al. 2019). PI 338046, a medium grain type, is another allelopathic rice variety that can be potentially used in an organic system (GRIN 2019). It is considered as one of the genetic sources for potential parental line in rice breeding worldwide (Agrama and Eizenga 2008). Weed suppressive varieties such as Rondo can provide weed control through production of more tillers and can be used in an organic rice system (Gealy and Yan 2012). Jasmine 85 is yet another weed suppressive rice variety that can be used as it substantially competes with weeds (Mahato et al. 2017).

Weed suppressive rice varieties are known to produce acceptable yields under conventional flooded rice systems but research on their weed suppressive potential and yield production in a flooded organic system is limited (Gealy et al 2003; Gealy et al. 2012). Their use as a much-needed tool of choice for weed control in organic systems have not been explored, especially for organic systems of Texas. Thus, the objectives of this research were to understand the response of selected weed species to the weed suppressive varieties tested, determine the yield potential of these weed suppressive rice varieties in an organic system in comparison to production with a minimum level of weed management (check plots), and to identify the best weed suppressive variety that produces acceptable yields equivalent to conventional rice production for organic rice producers of Texas.

Materials and methods

A small greenhouse experiment was established to understand the weed suppressive potential of selected rice varieties in a controlled environment. Weed seeds were planted with rice varieties to check whether allelopathy or competition is affecting weed growth. Field experiments were conducted to assess the weed suppressive potential of the selected rice varieties to weeds grown in a natural environment.

Greenhouse experiment. Rice weed seeds (Barnyard grass [*Echinochloa crus-galli* [L.] P. Beauv.); Amazon sprangletop [*Leptochloa panicoides* J Presl. Hitchc.]; hemp sesbania [*Sesbania herbacea* Mill. McVaugh]) were collected from rice fields in Wharton county, Texas in the summer of 2016. Rice varieties used in this study were provided by the United States Department of Agriculture - Agricultural Research Station (USDA-ARS) from Stuttgart, Arkansas. Previous research on weed suppression have utilized Rondo, PI 312777 and Jasmine 85; thus, these varieties were chosen for this experiment. Cocodrie and XL 753, the commercially cultivated varieties, were selected as a reference for non-weed suppressive checks (Table 3). Commercially used XL 753 variety used in this experiment was seed-treated. Hundred seeds of each rice variety selected and hundred seeds per species of weed were both planted linearly (9 cm space between the two populations) in plastic containers (34 cm x 21 x 12 cm in length, width, and height, respectively) inside a greenhouse facility at the Norman Borlaug Center, Texas A&M University, College Station, Texas such that each container was planted with a total of 100 weed seeds and 100 rice seeds. The planting lay out was designed to separate the weed species from rice varieties by a thin plastic film placed between in order to check if allelopathy was the reason if weed growth was affected (Falquet et al. 2014). Two independent experiments were conducted between June 13 and October 20, 2017 using a randomized complete block design with three replications. The rice varieties and weed species were planted on the same day in autoclaved soil to prevent bacterial infection and germination of other weed seeds. Pots were periodically irrigated to keep the soil moist. The number of weed seedlings that emerged were counted at 7, 14, and 21 days after planting (DAP).

Statistical analysis. Cumulative emergence data was converted into percentage values. Data was subjected to analysis of variance (ANOVA) using JMP (Version 13, SAS Institute Inc., Cary, N.C.), means separated using Fisher's Protected LSD (α=0.05). Cumulative emergence curves were plotted using Sigma Plot.

Field experiments. Field experiments were conducted for two seasons using different non-organic research sites each year at the David Wintermann Rice Research Station, Eagle Lake, Texas (29.37^{o}18^o N; 96.21^{o}55.2^o W), planted on 26 April, 2017 and 27 April, 2018. The soil at the experimental site was classified as a Crowley fine sandy loam. It was moderately acidic, with a sand, silt and clay content of 59, 24, and 17%, respectively. The soil nitrate-N, phosphorus, and potassium content were 6, 11, and 84 mg L^{-1}, respectively. The experiment was laid out in a randomized complete block design with four replications. Plot sizes were 5 m × 1.5 m.

Rice varieties used and seed establishment. Weed suppressive Indica rice varieties PI 312777, PI 338046, Jasmine 85 and Rondo were compared with the commercially grown varieties Cocodrie (inbred) and XL 753 (a long grain rice hybrid) for weed suppressive ability in terms of % weed infestation and crop yield (Table 3). Each variety was planted twice in each replication, one plot receiving weed control applications [weed-free; sprayed with Ricestar® (fenoxaprop-ethyl) {Bayer Crop Science, St. Louis, MO} post-flood @ 0.06 kg ai ha^{-1}] and the other receiving no weed control. All rice varieties were planted at a rate of 100 kg ha^{-1} except for XL 753 planted at 40 kg ha^{-1}. Seed planting depth was 2 cm. Rice seeds were dry-direct-seeded using a six-row drill-seed planter with 15 cm spacing. A weedy check (no rice) was also included for each rice variety. Weedy check plots were used to compare weed infestation of the experimental plots. The dominant weeds in the experimental site were broadleaf signalgrass (*Urochloa platyphylla*) (natural population), hemp sesbania and barnyardgrass (overseeded to diversify weed population). Fertilizer (N:P:K: 61:23:23 kg ha^{-1}) was incorporated into the soil using urea (46-0-0) and phosphorus + potassium (0-25-25) before planting. Flushed irrigation was done at 1, 8 and 14 days after planting. Permanent flood was introduced one month after planting.

Overall weed infestation data was gathered through visual assessments at 15, 45, and 90 DAP for each rice variety using a 0 to 100% scale (0%=no weed control and 100%=weed-free plot) in comparison to a weedy check. In 2018, due to severe infestation of broadleaf signalgrass (*Urochloa platyphylla* [Munro ex C. Wright] R. D. Webster), Ricestar ® (fenoxaprop-ethyl) [Bayer Crop Science, St. Louis, MO] was applied post-flood @ 0.06 kg ai ha^{-1}. Number of rice tillers were counted at 30 DAP. Rice grain yield was collected from a 4×1 m plot at harvest. Crop was mechanically harvested using a mini combine at maturity. Rice yield per hectare was adjusted based on the standard moisture content of 12%. Relative yield was calculated as a percent of the corresponding weed-free yield of each variety using the formula (Knezevic et al. 2003):

$$\left[\frac{[Yield(actual)]}{Yield(weedfree\ check)}\right] * 100$$

Weather information. Weather data was collected for both years of experimentation (Figure 8 & Table 4). Relative humidity was consistent in both years. The total rainfall during the cropping period in 2017 was 80.11 cm and in 2018 was 24.53 cm. The driest period in 2017 season was July (3.34 cm total rainfall) while in 2018 season was May (1.21 cm total rainfall) (Figure 8 & Table 4).

Statistical analysis. The normality and homogeneity of variances was tested using the Shapiro-Wilk and Bartlett's test, respectively. Data were transformed using the square-root transformation using the equation $\sqrt{x}$, where x is the visual injury rating. Transformed data did not improve homogeneity of variances. Data was subjected to analysis of variance (ANOVA) using JMP (Version 13, SAS Institute Inc., Cary, N.C.), means separated using Fisher's Protected LSD (α=0.05).

Results

Weed seedlings emergence pattern showed that weed species planted with the weed suppressive varieties emerged variably in response to the rice variety planted. Fields experiments revealed PI 312777 as the best performing weed suppressive rice variety in terms of reduced weed infestation and higher rice yield.

Amazon sprangletop. Regardless of variety, Amazon sprangletop did not emerge at 7 days after planting (DAP). Late emergence seems to be a characteristic trait of this species. When planted with PI 31277, it emerged at 20% and 60% levels at 14 and 21 DAP (Figure 9a). This was the lowest emergence recorded amongst all varieties tested.

When grown together with XL 753, Amazon sprangletop emerged at the highest rates (75% at 14 DAP and 98% at 21 DAP). Rondo allowed 60% and 85% emergence of weed seedlings at 14 and 21 DAP, respectively. Interestingly, Amazon sprangletop grown with Cocodrie had similar emergence (75%) with Jasmine 85 at 21 DAP.

Barnyardgrass. The weed suppressive varieties tested were able to delay the emergence of barnyard grass, as observed from the results of this experiment (Figure 9b). Though emergence of barnyardgrass was recorded at 7 DAP in Cocodrie and XL 753, the other varieties namely PI 312777, Jasmine 85 and Rondo did not have any emergence at 7 DAP and emerged seedlings count was recorded only at 14 DAP. At 21 DAP, barnyardgrass emergence in the weed suppressive varieties was 75 to 80% while in the commercial cultivated varieties viz., Cocodrie and XL 753, it was about 95%. Barnyardgrass had the least (50%) emergence in PI 312777 at 14 DAP compared to other varieties. It peaked to around 75% at 21 DAP, which was still the least recorded emergence value.

Hemp sesbania. Compared to Amazon sprangletop and barnyardgrass, the highest emergence of weed seeds at 7 DAP was recorded with hemp sesbania. Emergence of hemp sesbania with Cocodrie and XL 753 was very high early (95% at 7 DAP) and reached 100% at 14 DAP (Figure 9c). Even though the count of emerged hemp sesbania with weed suppressive varieties (PI 312777, Jasmine 85 and Rondo) was slightly better initially compared to Cocodrie and XL 753, the differences evened out with time and all varieties recorded a 100% emergence at 21 DAP. Rice variety PI 31277 recorded the lowest emergence count at 7 and 14 DAP, but the weed gained momentum and reached 100% emergence at 21 DAP. Hemp sesbania was an able competitor to rice as evidence from this study, even to weed suppressive varieties.

Tillering ability and crop maturity in the field experiment. When other weed control options were not used, varieties used in this experiment produced tillers ranging from 8 to 12 in 2017 and 9 to 14 in 2018. (Table 3). Weed suppressive variety PI 312777 produced equal number of tillers (12) during both years of study, while PI 338046 produced the lowest number (8) in 2017 and highest (14) in 2018. Tiller count was higher when the same varieties were cultivated under weed-free conditions (12 to 15 tillers in 2017 and 12 to 16 in 2018 - Table 3). The duration to maturity across rice varieties tested ranged between 96 and 113 days. XL 753 matured with shorter duration in both years (97 and 96 days) while the weed suppressive varieties, PI 312777, PI 338046, Jasmine 85 and Rondo, matured late (110 to 113 days duration), which was significantly higher.

Weed infestation. Weed infestation pertains to the overall density of weeds present in the plots at the time of evaluation by visual interpretation. Species-wise infestation rating was not done since broadleaf signalgrass took over as the primary weed in the experimental plots. Weed infestation was significant between years and hence, analyzed separately. The year by treatment interaction was not significant. In 2017, weed suppressive varieties PI 312777, PI 338046 and Jasmine 85 recorded 35 to 42% weed infestation at 15 DAP (Table 5). It was static at 35% for rice var. PI 338046 at 45 DAP but later increased to 60% at 90 DAP. PI 31277 was equally close in its suppressive ability recording 40% and 61% weed infestation at 45 and 90 DAP, respectively. Jasmine 85 also recorded lower weed infestation. This shows that, at different time periods of crop growth, the weed suppressive potential of the rice varieties tested, especially PI 338046 and PI 312777 was greater than the conventional varieties. Highest weed infestation was observed in XL 753 with 65%, 76% and 86% at 15, 45, 90 DAP in 2017, respectively. Cocodrie, an inbred variety, had high weed infestation similar to XL 753 during the entire season.

In 2018, weed infestation was high in Cocodrie and XL753 (70 and 72%) compared to the weed suppressive varieties (20 to 32%) at 15 DAP. At 45 DAP, similar to 2017, PI 338046 maintained its weed suppressive ability with only 35% infestation compared to the other adaptable varieties (43 to 46% - PI 312777 and Jasmine 85). Rondo had higher weed infestation amongst the suppressive varieties at 61%. At 90 DAP, weed infestation among the weed suppressive varieties ranged from 60 to 75%. XL 753 and Cocodrie however, had very high weed infestation (85 to 94%).

Relative grain yield. With the year effect on relative grain yield significant, it was analyzed separately for both years. Relative yield was least affected in PI 312777 (yield level of 81%) followed by PI 338046 (45%) compared to all other varieties (Figure 10a) in 2017. Higher weed infestation affected the yield of non-weed suppressive varieties. Cocodrie recorded the least relative yield (30%) among the varieties tested. Contrary to expectations, Rondo did not perform well, and the presence of weeds reduced the yield levels of this variety.

Despite a warmer weather in 2018 (Figure 8 and Table 4), relative yield was generally low due to high infestation of broadleaf signalgrass. Rice var. PI 312777 had the highest relative yield (60%) across the varieties tested (Figure 10b) revealing its potential to be a weed suppressive cultivar that could hold and yield well under organic rice systems with limited weed management tools. The relative yield of other varieties namely, Jasmine 85, PI 338046, Rondo, Cocodrie and XL 753 ranged between 20 and 35% under organic production with no weed management.

Discussion

Weed species tested under greenhouse conditions differed in their response to rice varieties. The greenhouse study aimed to separate allelopathy from competition. However, the three weed species tested emerged regardless of the variety grown indicating that the rice varieties used were only weed suppressive and not allelopathic to the extent of non-emergence. Field experiments also indicated a similar response to weed infestation. Barnyardgrass, the most problematic weed in rice, had the highest emergence in the XL753 pots. This was expected since XL 753 is a commercially grown cultivar that does not have weed suppressive potential and barnyard grass thrives in a rice environment using the C4 pathway, especially if there is little to no weed control in the field (Bagavathiannan et al. 2012). Similarly, XL 753 was the highly weed infested plot in the field during both years of study followed by Cocodrie. This might be because both are commonly grown commercial varieties that have no weed suppressive potential. On the contrary, PI 338046 was the least infested plot closely followed by PI 312777. The same rice variety, PI 312777, also recorded reduced weed emergence in the green house experiment. Gealy et al (2010), in their study with PI 312777, attribute this to the weed suppressive and allelopathic potential, which can slow down the growth of grassy weed species such as barnyardgrass and Amazon sprangletop. Hemp sesbania had a 100% emergence in all rice varieties tested, including the weed suppressive ones under greenhouse conditions. This shows rice variety PI 312777 to be suitable to organic systems of Texas.

Indica varieties used in our study (PI 312777, Jasmine 85 and Rondo) have been previously tested and confirmed to have weed suppressive characteristics resulting in lower weed emergence of grassy species (Gealy et al. 2014; Marchetti et al. 1998; Yan and McClung 2010). Our field experiments confirm this with respect to PI 312777 and Jasmine 85. However, Rondo did not perform similarly. The increased weed infestation in plots with Rondo compared to other Indica varieties could be explained by the fact that the number of tillers recorded per plant was lower. This may have reduced the competition to weeds. Contrary results of higher tillering and improved weed suppression through competition in rice variety Rondo has been reported by Gealy and Yan (2012). Allelopathic studies in sorghum (*Sorghum bicolor* L.) showed that it produces a compound sorgoleone that inhibits the photosystem II (PS II) pathway necessary for the evolution of oxygen during photosynthesis (Rimando et al. 1998) thereby affecting growth. However, allelopathic rice varieties form a different compound called momilactone B. PI 312777 has three known compounds that increases the rice plant defenses to pathogens: 3-isopropyl-5-acetoxycyclohexane-2-one-1, 5,7,4'-trihydroxy-3',5'-dimethoxyflavone, and momilactone B (Kong et al. 2004). Momilactone B is developed in the rice system as a defense mechanism resulting in the suppression of nearby plant growth (Kato-Noguchi 2004; Osbourn 2010). Mattice et al.

(2001) reported the presence of this allelopathic compound in PI 338046 and Patni et al. (2018) reported it to be the cause that affects the emergence of weed seeds, especially when it belonged to the Poaceae family. The weed suppressive property of PI 312777 rice variety used in this experiment can potentially delay the weed seedling emergence as shown in our greenhouse experiment and corroborated by the results of the field experiments too. Moreover, our greenhouse study indicates that weed suppression is dependent on the weed species and population present in the field. Broadleaves such as hemp sesbania can outgrow rice regardless of the variety. The ability of hemp sesbania to withstand unfavorable biotic and abiotic conditions during germination allows the weed to survive unless chemical weed control or early canopy closure is achieved in rice (Street and Mueller 1993). Grass species such as barnyardgrass are more prone to weed suppression especially in PI 312777 rice variety (Gealy et al. 2003).

With organic production systems, it is necessary to assess the performance of weed suppressive cultivars for adaptability and profitability. Rice production greatly depends on the ability of the crop to produce optimum tillers. Existing weather conditions are also crucial in tiller development. Higher temperature and drier moisture conditions contributed to increased tiller production in 2018 crop season. Temperature potentially influences tiller production of rice which in turn is related to crop yield. Research reports that rice plants subjected to heat treatment grown under high night temperature produced more tillers (Mohammed and Tarpley 2010). A previous study conducted by Wu et al. (1998) relates tiller production positively to yield. Though conditions (temperature and tillers) were optimum for production, high weed pressure through increased weed infestation in 2018 lowered the relative yield levels regardless of the number of tillers in our experiment. Gealy and Yan (2012) indicated that tiller production in weedy conditions was correlated to yield loss in the case of varieties such as Rondo and PI 312777 even with minimal herbicide inputs, which validate our results. When compared to weed free tiller count, weedy conditions had lower tiller number in Rondo, Cocodrie and XL 753 resulting in lower relative yield. However, there was not much reduction in the number of tillers in weed suppressive varieties *viz*., PI 31277, PI 338046 and Jasmine 85 under weedy conditions. Our rice yield results are in harmony with the research models of competition and yield ability in the presence of weeds by de Vida et al. (2006). They state that the rice yield produced has positive correlation with the late-season biomass production. Early in the season (21 DAP), our crop had minimal weed pressure (Figure 11). However, as the cropping season progressed, rice was still competing with the weeds. Weed pressure increased which may have resulted in higher tillering of the weed suppressive rice varieties rather than yield production.

In our study, high weed infestation from 45 to 90 DAP was a critical factor in crop yield. For the weed suppressive rice varieties, the infestation was higher during the 45 to 90-day period while for the commercial cultivated varieties used like Cocodrie and XL 75, the weed emergence and infestation was higher even at 15 DAP, and increasing thereon. Most of hemp sesbania, barnyardgrass and broadleaf signalgrass were able to survive until harvest (Figure 12). Several factors can be attributed to the yield differences in between years. First, the possibility of late-season rice competitiveness could cause a higher yield penalty due to higher respiration that lowers the photosynthetic process at maturity (de Vida et al. 2006) resulting in lower allocation to the sink, and also extending tillering instead of allocating the resources to yield. Second, environmental factor can be attributed to the yield difference such as the weather. The existing weather was different between the two years during field experimentation. Weather can also influence the rice yield at harvest especially in drier conditions. During dry or warmer weather rice plants are prone to spikelet sterility (Satake and Yoshida 1978). Rice spikelet sterility can occur at temperatures over 35^{o} C resulting from lower number of pollen production (Matsui et al. 1997). This might also have contributed to the decrease in crop yield apart from weed infestation and competition.

PI 312777 is a promising Indica variety that can be used in an organic rice production system in addition to Rondo and Jasmine 85 (Gealy and Yan 2012). In our study, PI 312777 exhibited beneficial weed suppressive characters and higher rice yields (weed suppressive and commercial) during both years, making it a viable option for weed control in organic rice production in Texas. Rice variety PI 312777 therefore, is a viable weed suppressive varietal option that also produces acceptable yields in organic systems. Moreover, such weed suppressive rice varieties can be further bred into elite high yielding lines since these already are sources of parent material in developing new rice cultivars (Agrama and Eizenga 2008). Yield performance experiments in the US Midsouth also suggest that weed suppressive rice varieties (Rondo and Jasmine) can produce yields similar to commercial rice varieties such as Cocodrie, Francis and Wells (Yan and McClung 2010). However, consideration of all factors of rice production is necessary to achieve such acceptable yields in an organic system. Therefore, understanding the role of biotic and abiotic factors such as weather conditions and the infestation and density of weed species during the reproductive phase of rice is important as it can impact the yield at harvest.

Conclusion

Rice production in an organic system does not have the options of a conventional production system for weed control. Weed suppressive rice varieties can bridge this gap as a viable option for weed control in organic systems. Most research on weed suppression and yield performance of weed suppressive varieties has been conducted in conventional rice production systems, with very few to almost none on organic systems of Texas, where majority of the organic rice is produced in the US. There is a paucity of information on use of weed suppressive varieties as a tool for weed control and hence this study was conducted to provide that information. Results of the green house studies with varieties PI 312777, Jasmine 85, Rondo in comparison to Cocodrie and XL 753 showed that Amazon sprangletop, barnyardgrass, and hemp sesbania had different emergence response to weed suppressive varieties. Adoption of PI 312777, an Indica rice variety that has weed suppressive potential lowered the seedling emergence of grass species. Hemp sesbania can be a problematic weed in organic rice in Texas regardless of the rice variety grown. Among the rice varieties used, PI 312777, PI 338046, and Jasmine 85 can suppress weed growth. However, PI 312777 comes out as the best performing variety in this study in terms of yield maintenance and weed suppression achieved and can be recommended for use in organic rice production systems. Rice yield performance of weed suppressive varieties vary with location. Therefore, further field testing for yield is required, in particular, on certified organic field sites to support the growing organic rice industry. Weed suppressive varieties provide organic rice growers, particularly in Texas, options to minimize costs incurred in controlling weeds and an effective weed management strategy. Furthermore, additional weed control strategies such as flood management and non-synthetic herbicides have to be supplemented for improved rice yields in an organic system.

References

Agrama HA, Eizenga GC (2008) Molecular diversity and genome-wide linkage disequilibrium patterns in a worldwide collection of Oryza sativa and its wild relatives. Euphytica 160:339-355

Bagavathiannan MV, Norsworthy JK, Smith KL, Neve P (2012) Seed production of barnyardgrass (*Echinochloa crus-galli*) in response to time of emergence in cotton and rice. J. Agric. Sci. 150:717-724

Bagavathiannan, MV, Norsworthy JK, Jha P, Smith K (2011) Does resistance to propanil or clomazone alter the growth and competitive abilities of barnyardgrass (*Echinochloa crus-galli*)? Weed Sci. 59:353-358

Barnaby JY, Rohila JS, Henry CG, Sicher RC, Reddy VR, McClung AM (2019) Physiological and metabolic responses of rice to reduced soil moisture: relationship of water stress tolerance and grain production. Int. J. Mol. Sci. https://doi.org/10.3390/ijms20081846

Baumann, DT, Bastiaans L, Kropff MJ (2001) Competition and crop performance in a leek–celery intercropping system. Crop Sci. 41:764-774

Brabham C, Norsworthy JK, Sandoski CA, Varanasi VK, Schwartz-Lazaro LM (2019) Spray deposition, adjuvants, and physiochemical properties affect benzobicyclon efficacy. Weed Technol. 33: 258-262

Campanelli G, Testani E, Canali S, Ciaccia C, Leteo F, Trinchera A (2019) Effects of cereals as agro-ecological service crops and no-till on organic melon, weeds and N dynamics. Biol. Agric. Hortic. 1:1-13

Chauhan BS, Abugho SB (2013) Effect of crop residue on seedling emergence and growth of selected weed species in a sprinkler-irrigated zero-till dry-seeded rice system. Weed Sci. 61:403-409

Chauhan BS, Awan TA, Abugho SB, Evengelista G (2015) Effect of crop establishment methods and weed control treatments on weed management, and rice yield. Field Crops Res. 172:72-84

Chauhan, BS (2012) Weed ecology and weed management strategies for dry-seeded rice in Asia. Weed Technol. 26:1-13

Cheng HH (1992) A conceptual framework for assessing allelochemicals in the soil environment. In: Rizvi SJH; Rizvi V (Eds.) Allelopathy-basic and applied aspects. Chapman Hall, New York

de Vida FBP, Laca EA, Mackill DJ, Fernández GM, Fischer AJ (2006) Relating rice traits to weed competitiveness and yield: a path analysis. Weed Sci. 54:1122-1131

Delmotte S, Tittonell P, Mouret JC, Hammond R, Lopez-Ridaura S (2011) On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate. Europ. J. Agron. 35: 223-236

Falquet B, Roux D, Henriet L, Tschuy F, Wirth J (2014) Simple method to separate resource competition from allelopathic root interactions. Allelopathy J. 34:227-240

Franco JG, King SR, Masabni JG, Volder A (2018) Intercroppped watermelon for weed suppression in a low-input organic system. HortTechnol. 28:172-181

Gealy D, Ottis B, Talbert R, Moldenhauer K, Yan W (2005) Evaluation and improvement of allelopathic rice germplasm at Stuttgart, Arkansas, USA. In Proceedings of the 4th World Congress on Allelopathy, Wagga Wagga, NSW, Australia: International Allelopathy Society, pp. 157-163

Gealy DR, Anders M, Watkins B, Duke S (2014) Crop performance and weed suppression by weed-suppressive rice cultivars in furrow-and flood-irrigated systems under reduced herbicide inputs. Weed Sci. 62:303-320

Gealy DR, Wailes EJ, Estorninos LE, Chavez RSC (2003) Rice cultivar differences in suppression of barnyardgrass (*Echinochloa crus-galli*) and economics of reduced propanil rates. Weed Sci. 51:601-609

Gealy DR, Yan WD (2012) Weed suppression potential of ‘Rondo’and other indica rice germplasm lines. Weed Technol. 26: 517-524

Germplasm Resources Information Network (GRIN) (2019) US National Plant Germplasm System. https://npgsweb.ars-grin.gov/gringlobal/accessiondetail.aspx?id=1233406. Accessed: September 13, 2019

Gheshm R, Brown RN (2018) Organic Mulch Effects on High Tunnel Lettuce in Southern New England. HortTechnol. 28:485-491

Isik D, Kaya E, Ngouajio M, Mennan H (2009) Weed suppression in organic pepper (*Capsicum annuum* L.) with winter cover crops. Crop Prot. 28:356-363.

Jennings PR, Aquino RC (1968) Studies on competition in rice. III. The mechanism of competition among phenotypes. Evolution 22:529-542

Kato-Noguchi H (2004) Allelopathic substance in rice root exudates: Rediscovery of momilactone B as an allelochemical. J. Plant Physiol. 161:271-276

Kent RJ, Johnson DE (2001) Influence of flood depth and duration on growth of lowland rice weeds, Cote d'Ivoire. Crop Prot. 20:691-694

Knezevic SZ, Evans SP, Mainz M (2003). Row spacing influences the critical timing for weed removal in soybean (Glycine max). Weed Technol. 17:666-673

Kong C, Liang W, Xu X, Hu F, Wang P, Jiang Y (2004) Release and activity of allelochemicals from allelopathic rice seedlings. J. Agric. Food Chem. 52:2861-2865

Liebman M, Bastiaans L, Baumann DT (2004) Weed management in low-external-input and organic farming systems In Inderjit (Ed) Weed Biology and Management. The Netherlands: Dordrecht

Mahato GR, McClung AM, Ntamatungiro S, Singh S, Pokharel M, Wiley V, Huang B (2017) Preliminary Trial of Cover Cropping and Weed Control for Organic Rice. Amer. J. Plant Sci. 8:2758

Marchetti MA, Bollich CN, Webb BD, Jackson BR, McClung AM, Scott JE, Hung HH (1998) Registration of 'Jasmine 85'rice. Crop Sci. 38:896

Mattice JD, Dilday RH, Gbur EE, Skulman BW (2001) Barnyardgrass inhibition with rice using high-performance liquid chromatography to identify rice accession activity. Agronomy J. 93: 8-11

Mir SA, Bosco SJD (2014) Cultivar difference in physicochemical properties of starches and flours from temperate rice of Indian Himalayas. Food Chem. 157:448-456

Mohammed AR, Tarpley L (2010) Effects of high night temperature and spikelet position on yield-related parameters of rice (*Oryza sativa* L.) plants. Europ. J. Agron. 33:117-123

Mouret JC, Hammond R, Dreyfus F, Desclaux D, Marnotte P, Mesleard F (2004) An integrated study of the development of organic rice cultivation in the Camargue (France). http://orgprints.org/6492/1/turin-riz.pdf. Accessed October 31, 2019

Norsworthy JK, Fogleman M, Barber T, Gbur EE (2019) Evaluation of acetochlor-containing herbicide programs in imidazolinone-and quizalofop-resistant rice. Crop Prot. 122:98-105

Osbourn A (2010) Gene clusters for secondary metabolic pathways: an emerging theme in plant biology. Plant Physiol. 154:531-535

Osterholt MJ, Webster EP, Blouin DC, McKnight BM (2019) Overlay of residual herbicides in rice for improved weed management. Weed Technol. 33: 426-430

Pan XB, Rush MC, Sha XY, Xie QJ, Linscombe SD, Stetina SR, Oard JH (1999) Major gene, nonallelic sheath blight resistance from the rice cultivars Jasmine 85 and Teqing. Crop Sci. 39:338-346

Patni B, Chandra H, Mishra AP, Guru SK, Vitalini S, Iriti M (2018) Rice allelopathy in weed management- an integrated approach. Cell. Mol. Biol. 8:84-93

Peruzzi A, Ginanni M, Fontanelli M, Raffaelli M, Bàrberi P (2007) Innovative strategies for on-farm weed management in organic carrot. Renew. Agrl. Food Sys. 22:246-259

Reganold JP, Wachter JM (2016) Organic agriculture in the twenty-first century. Nature Pl. 2:1-8

Rimando AM, Dayan FE, Czarnota MA, Weston LA, Duke SO (1998) A new photosystem II electron transfer inhibitor from Sorghum bicolor. J. Nat. Prod. 61:927-930

Street JE, Mueller TC (1993) Rice (Oryza sativa) weed control with soil applications of quinclorac. Weed Technol. 7:600-604

Telo GM, Webster EP, Blouin DC, McKnight BM, Rustom SY Jr (2019) Florpyrauxifen-benzyl activity on perennial grass weeds found in Louisiana rice production. Weed Technol. 33:246-252

United States Department of Agriculture- National Agriculture Statistics Service (2017) Certified organic survey. https://downloads.usda.library.cornell.edu/usda-esmis/files/zg64tk92g/70795b52w/4m90dz33q/OrganicProduction-09-20-2017_correction.pdf. Accessed: September 3, 2019

United States Department of Agriculture- National Agriculture Statistics Service (2019) National Statistics for rice. https://www.nass.usda.gov/Statistics_by_Subject/ result.php?E9031EEA-0EFF-3004-A14F-C9BDA6525FAE&sector =CROPS&group=FIELD%20CROPS&comm=RICE. Accessed November 22, 2019

Xu K, Ismail AM, Ronald P (2013) Flood tolerance mediated by the rice Sub1A transcription factor. Plant Abiotic Stress 1:1-13

Yan WG, McClung AM (2010) Rondo, a long-grain indica rice with resistances to multiple diseases. J. Pl. Reg. 4:131-136

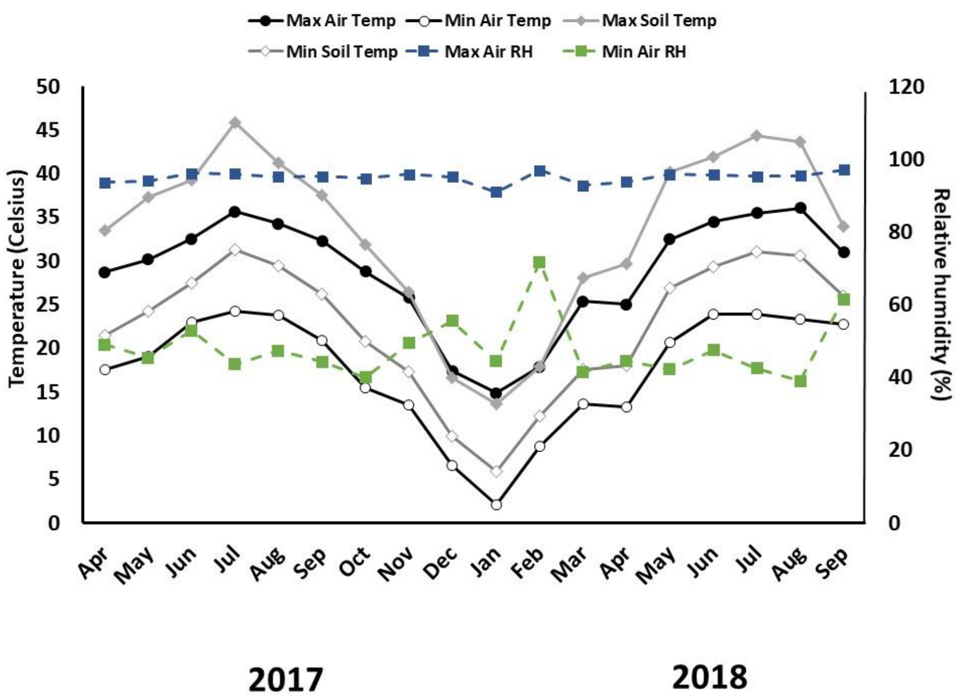
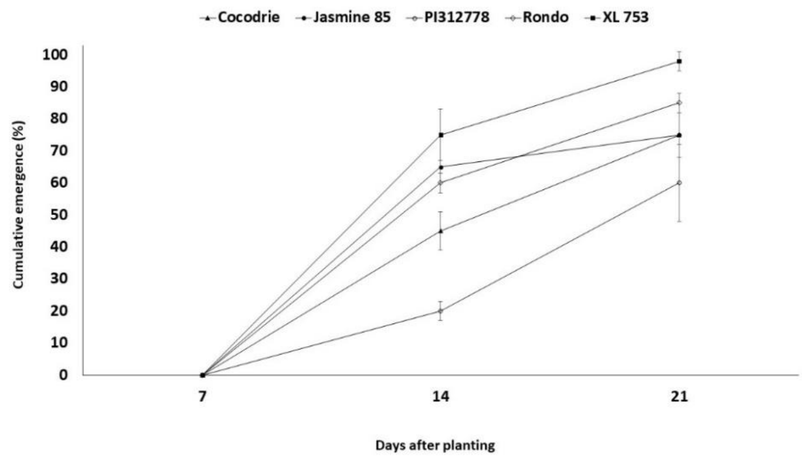
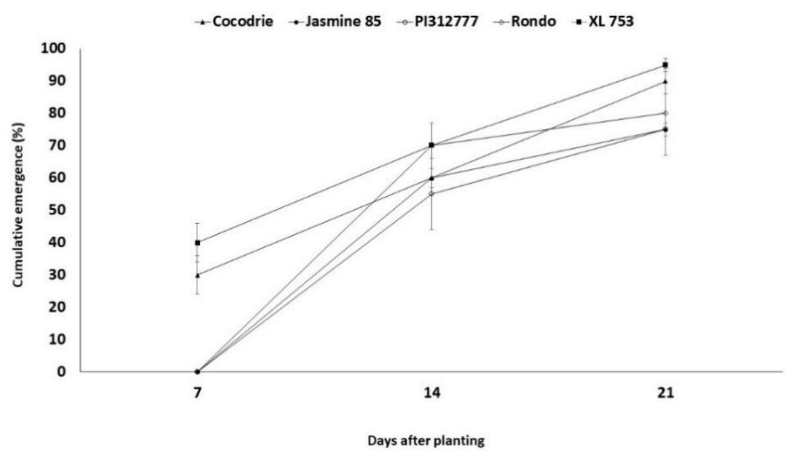


Figure 8. Air temperature, soil temperature, and relative humidity values at the research site in 2017 and 2018, David Wintermann Rice Research Station, Eagle Lake, Texas.

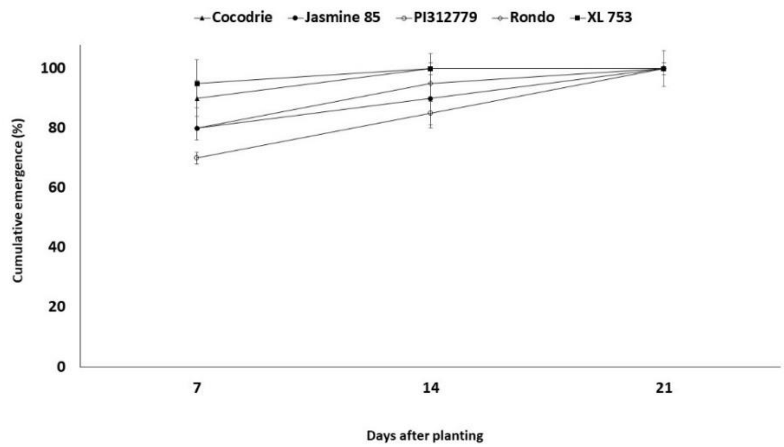


A



B

Figure 9. Cumulative emergence percentage of A) Amazon sprangletop, B) barnyardgrass, and C) hemp sesbania grown in mixture with Cocodrie, PI 312777, Jasmine 85, Rondo and XL753



C

Figure 9 Continued.

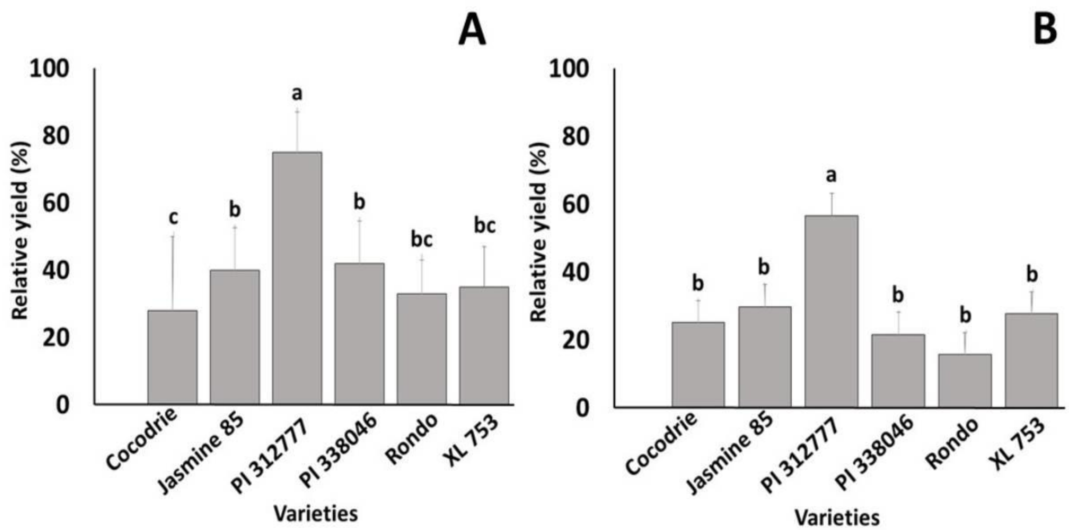


Figure 10. Yield of different rice varieties (%) under weed interference, relative to the weed-free check in A) 2017 and B) 2018 at the David Wintermann Rice Research Station, Eagle Lake, Texas[a]

[a]Means separated using Fisher's Protected LSD (α=0.05).

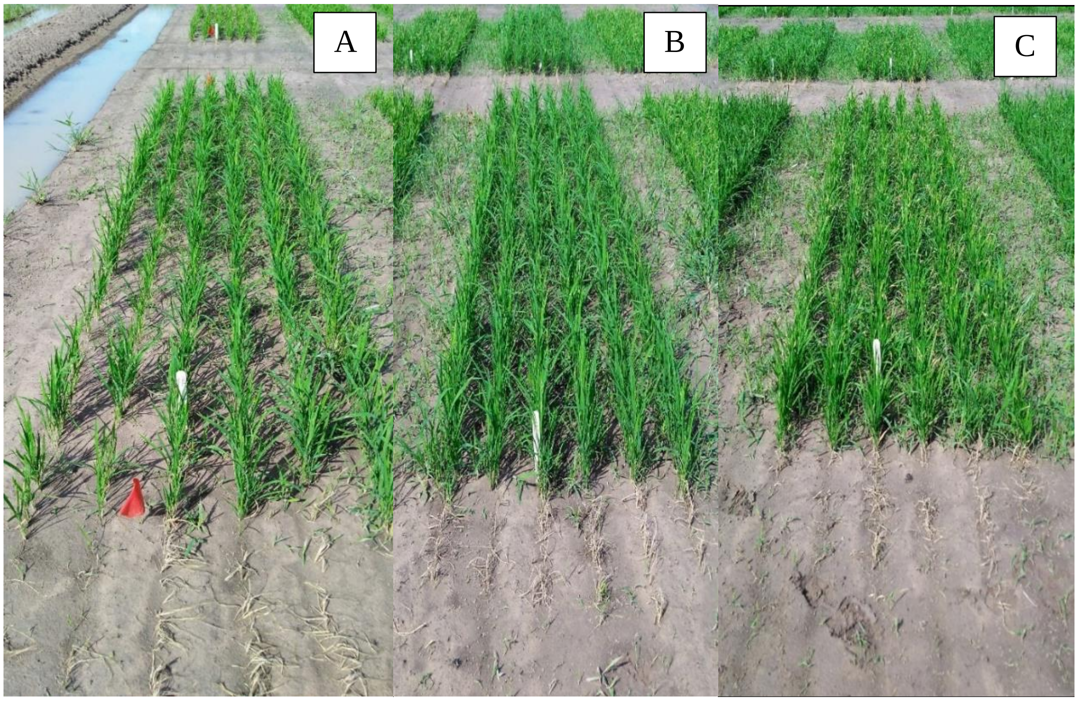


Figure 11. Visual differences on weed infestation in A) PI 312777, B) Jasmine 85, and C) PI338046 at 21 days after planting

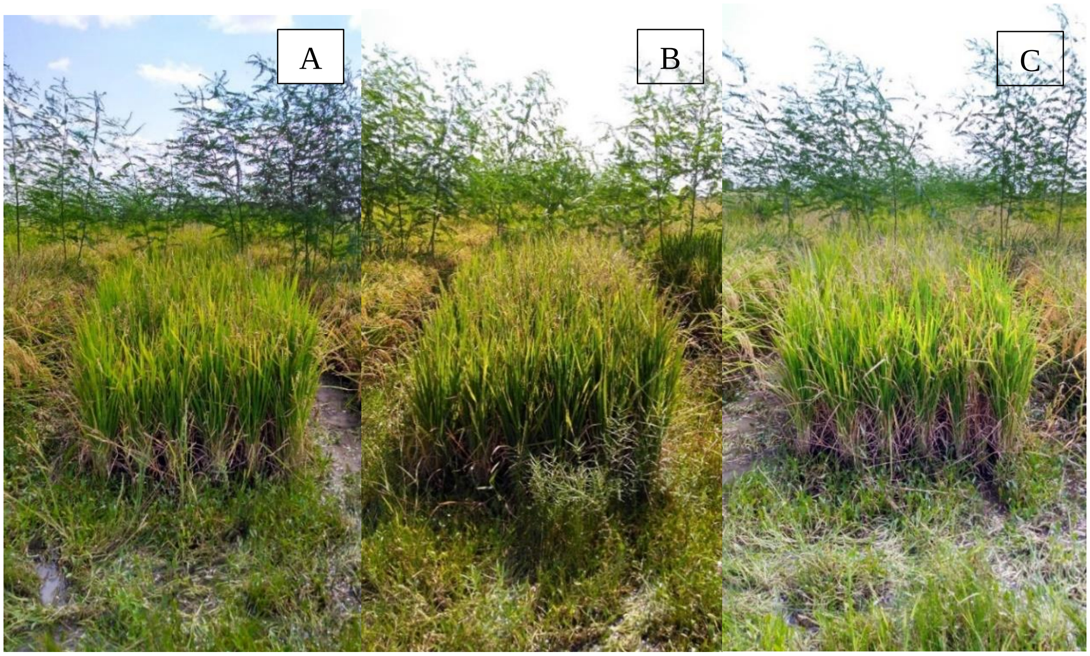


Figure 12. Visual differences on weed infestation in A) PI 312777, B) Jasmine 85, and C) PI 338046 at harvest.

Table 3. Rice variety information at the David Wintermann Rice Research Station, Eagle Lake, Texas[a]

Rice	Grain type			Particulars							
				Maturity[b]		Weed-free tiller count[c]		Weedy tiller count[c]		Weed-free yield[d]	
				2017	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
				days		no. plant^{-1}		no. plant^{-1}		metric tons ha^{-1}	
Cocodrie	Long	Indica	Non-supressive	100	103	13(3)a	15(1)a	10(4)a	9(1)a	7.79(0.4) a	5.92(0.64) b
Jasmine 85	Long	Indica	Weed suppressive	113	113	15(2)a	12(2)a	11(4)a	11(2)a	0.63(0.1) c	6.2(0.23) ab
PI 312777	Short	Indica	Allelopathic	113	113	12(3)a	12(1)a	12(6)a	12(3)a	2.39(0.5) b	5.15(0.3) bc
PI 338046	Medium	Indica	Allelopathic	113	113	14(2)a	13(2)a	8(1)a	14(5)a	1.41(0.2) bc	4.41(0.4) c
Rondo	Long	Indica	Weed suppressive	113	110	15(2)a	16(2)a	12(5)a	10(1)a	1.23(0.3) bc	6.06(0.7) ab
XL 753	Long	Indica	Non-suppressive	97	96	15(1)a	14(1)a	11(5)a	11(2)a	8.78(0.9) a	7.47(0.1) a

[a]Means separated using Fisher's protected LSD ($\alpha = 0.05$).
[b]Days to complete maturity among the rice varieties in 2017 and 2018
[c]Tiller count at 30 days after planting. Standard error in parenthesis.
[d]Rice yield was mechanically harvested. Standard error in parenthesis.

Table 4. Monthly rainfall, solar radiation and evapotranspiration averages during the rice growing season in 2017 and 2018 at the David Wintermann Rice Research Station, Eagle Lake, Texas

Month	**2017**			**2018**		
	Rainfall[a]	**Evapotranspiration**[b]	**Solar radiation**[c]	**Rainfall**	**Evapotranspiration**	**Solar radiation**
	cm	**mm day^{-1}**	**MJ m^{-2} day^{-1}**	**cm**	**mm day^{-1}**	**MJ m^{-2} day^{-1}**
April	4.76	4.3	19.89	8.04	3.9	18.80
May	5.03	4.6	20.67	1.21	4.8	21.58
June	18.83	4.7	21.39	12.44	4.9	21.86
July	3.34	5.4	24.58	5.88	5.2	23.77
August	52.91	4.4	18.72	5.00	4.9	21.06
September	4.02	4.1	18.58	21.25	3.0	13.51

[a]Total monthly rainfall in cm.
[b]Mean evapotranspiration rate per day .
[c]Mean solar radiation per day.

Table 5. Overall weed infestation (area %) in 2017 and 2018 at the David Wintermann Rice Research Station, Eagle Lake, Texas[a]

Variety	**Weed infestation**					
	2017			**2018**		
	15 DAP[b]	45 DAP	90 DAP	15 DAP	45 DAP	90 DAP
	--%--					
Cocodrie	61 (18) ab	61 (10) ab	76 (10) ab	70(15) a	61(30) ab	85 (18) a
Jasmine 85	42 (1) b	46 (5) bc	63 (4) b	32(7) b	46(5) bc	63 (8) b
PI 312777	37 (5) b	40 (4) bc	61 (5) b	22(17) b	43(13) bc	63 (13) b
PI 338046	35 (7) b	35 (16) c	60 (6) b	26(11) b	35(1) c	60 (10) b
Rondo	55 (18) ab	61 (10) ab	75 (8) ab	20(5) b	61(17) ab	75 (17) b
XL 753	65 (22) a	76 (24) a	86 (20) a	72(15) a	76 (30) a	94 (12) a

[a] Broadleaf signalgrass (85%), hemp sesbania (10%), and barnyardgrass (5%) were the dominant weed species. Means separated using Fisher's protected LSD ($\alpha = 0.05$).

[b]Abbreviations: DAP, days after rice planting.

CHAPTER IV

NON-SYNTHETIC HERBICIDES FOR WEED CONTROL IN ORGANIC RICE

Introduction

Organic rice (*Oryza sativa* L.) is considered as a specialty crop commodity contributing to the US economy (USDA-NASS 2017). Organic rice production contributed $42.7 M in the US economy and Texas, the leading organic rice producing state had $13.7 M out of the total US value in 2016 (USDA-NASS 2017). Commercial organic rice is mainly produced in the Southeastern part of Texas. Nevertheless, organic rice certification is necessary for a Texas rice producer wishing to adopt organic production mandated by the state and federal department of Agriculture (Texas DA 2019; USDA 2019). The federal government mandated the Organic Food Production Act section 2109 not allowing any synthetic fertilizer or pesticide application to achieve organic certification (US Government 1990). The mandate advocates the benefits of organic production to the environment such as less fossil fuel consumption, increased soil, health, and reduced use of synthetic herbicides (Arnhold et al. 2014; Bond and Grundy 2001; Williams and Hammitt 2001). Due to the increased awareness of the benefits of organic production to the environment and increased profit, regulations are necessary to be implemented to achieve the high standards for consumption, including organic rice (Raynolds 2000; IFOAM 2016).

Nevertheless, weeds are the number problem in a rice production system. Oerke and Dehne (2004) reported that weeds contribute up to 35% potential yield loss in rice. Weeds adapt to different crop environments prompting an effective weed management program to avoid yield loss in organic rice (Bagavathiannan and Norsworthy 2012; Riar and Norsworthy 2011). Most of the problematic weed species in rice are grassy weed species. Barnyardgrass (*Echinochloa crus-galli* [L.] P. Beauv.), a grassy weed species in rice, potentially reduces rice yield 2000 to 4000 kg ha^{-1} (Mitich 1990). Continuous rice monocropping is one of the causes of barnyardgrass infestation in rice (Bagavathiannan et al. 2014). Other grassy species infesting rice in Texas include weedy rice (*Oryza sativa* L.) junglerice [*Echinochloa colona* (L.) Link] and Nealley's sprangletop (*Leptochloa nealleyi*) (Liu 2018; Bergeron et al. 2015). A potential problematic broadleaf weed in organic rice is hemp sesbania ([*Sesbania herbacea* (Mill.) McVaugh], currently ranked in the top ten problematic weed species in MidSouthern US rice production (Norsworthy et al. 2013). Weed management in organic system is very challenging and, left uncontrolled can result to high yield losses in organic rice (Liebman and Davis 2009; Kong et al. 2008). Few available tools are currently used in organic rice. These tools include flooding, the use of allelopathic/weed suppressive rice varieties, and the use of implements (mechanical-weeding) (Kent and Johnson 2001; Mouret et al. 2004; Kong et al 2008). Non-synthetic herbicides offer additional set of tools in weed management in organic rice on these circumstances.

Non-synthetic herbicides, some are plant extract based, caters to a smaller market of crop protection tools and serves as an alternative to synthetic herbicides in controlling weeds (Abouziena et al. 2009; Pachlatko 1998). Most non-synthetic herbicides are used as burndown in organic systems due to their broad spectrum weed control (Diver et al. 2008; Gunderson et al. 2008). Although majority of non-synthetic herbicides have contact activity, these herbicides can have different site of action in the plant and have simpler chemical template structures often used for synthetic herbicides (Dayan et al. 2012). The Organic Materials Research Institute (OMRI) reviews and certifies non-synthetic herbicides prior to commercial use in an organic production system (OMRI 2019). Dayan et al. (2009) summarized a list of non-synthetic herbicides used in an organic system in the late 2000s. Recently, Baker and Grant (2018) compiled an in-depth report involving site of action, toxicity and efficacy of non-synthetic herbicides. In this study, we focused on acetic acid (vinegar), caprylic acid, clove oil, cinnamon oil, citric acid, and corn gluten meal as potential non-synthetic herbicides in rice. Vinegar (acetic acid), a non-selective contact herbicide is used in weed control in sweet corn, potatoes and onion (Evans and Bellinder 2009). High concentrations of acetic acid causes dissolution of cell membranes leading to plant dessication (Gunderson et al. 2008). A diluted solution (20%) of vinegar is commercially available used as broad spectrum weed control (Dayan et al. 2009). Another non-synthetic herbicide is corn gluten meal, derived from wet-milled corn, usually incorporated into the soil and serve as a preemergence herbicide (Baker and Grant 2018). Although primary used as a livestock feed for cattle, horses, and pigs, corn gluten meal serve as a non-synthetic herbicide inhibiting the germination of small seeded weeds (Baker and Grant 2018; Gunderson et al. 2008). Hydrolysis of corn gluten meal in the soil releases toxic dipeptides in the affecting the cell membrane integrity (Dayan et al. 2009). Citric acid and clove oil are non-synthetic herbicides that can be used as fungicide and insecticide. Citric acid, usually found in *Citrus* spp., is an acid component of the Krebs cycle and is commercially produced through the process of fermentation (Baker and Grant 2018). Clove oil, derived from buds of the tropical evergreen (*Syzygium aromaticum* L.), acts as a cell-membrane disruptor, and usually applied as post-emergent-nonselective herbicide (Baker et al. 2018). Clove oil contains eugenol and other terpenoids, compounds known to disrupt the cytoplasmic membrane of cells inhibiting specific cellular processes (Wendakoon and Sakaguchi 2005; Kwon et al. 2003) Cinnamon oil, derived from cinnamon (*Cinnamomum verum* L.) through distillation, can be used as an enhancer to clove oil for herbicide purposes (Hsu et al. 2012; Baker et al 2018). Baker et al. reports that cinnamon oil can be an effective herbicide to grasses such as johnsongrass, Caprylic acid, derived from coconut oil, is a saturated medium-chain fatty acid that can be used as an effective nonselective herbicide (Coleman and Penner 2008; Santos et al. 2011). Coleman and Penner (2008) reports that caprylic acid is generally safe and used as crop dessicant or harvest aids to potato (*Solanum tuberosum* L.), alfalfa (*Medicago sativa* L.) and cotton (*Gossypium hirsutum* L.).

Non-synthetic herbicides combined with other weed practices in offers additional .management tools in organic rice. Although there are studies on the efficacy of non-synthetic herbicides in certain weed species in organic crop production systems and nurseries, limited information is available on how these herbicides perform on dominant weed species in rice (Abouziena et al. 2009; Dayan and Duke 2010; Chappell et al. 2012). Furthermore, no crop safety data in rice is available using non-synthetic herbicides. Therefore, the objectives of this research were 1) to assess the tolerance of rice to labeled rates of non-synthetic herbicides applied at two rice stages, 2) evaluate the efficacy of weed control of selected non-synthetic herbicides to ivyleaf morningglory (*Ipomoea hederacea* L), Palmer amaranth (*Amaranthus palmeri* L.), hemp sesbania, barnyardgrass, broadleaf signalgrass (*Urochloa platyphylla* L.), large crabgrass (*Digitaria sanguinalis* L.), and yellow nutsedge (*Cyperus esculentus* L.) and 3) identify the best non-synthetic herbicide controlling weeds without negative impact to growth and yield or organic rice. The study hypothesizes that labeled rates of non-synthetic herbicides controls weeds without impacting rice growth and development.

Materials and methods

A greenhouse experiment was conducted for preliminary responses of weeds and rice to non-synthetic herbicides under a controlled environment. Field experiments were conducted in two sites: 1) non-organic research site and 2) a certified organic farm both located at Eagle Lake Texas in 2018 to 2019.

Greenhouse experiment. A greenhouse experiment was conducted at the Norman Borlaug Center in June 1, 2018 to December 10, 2018 in Texas A&M University, College Station, Texas to assess the rice injury and weed control efficacy of non-synthetic chemicals. The study was conducted in a completely randomized design with three replications. Seven non-synthetic herbicides certified through the Organic Materials Review Institute (OMRI) were used and compared with a nontreated check (Table 6).

Five seeds of barnyardgrass, large crabgrass, broadleaf signalgrass (*Urochloa platyphylla*), Nealley's sprangletop (*Leptochloa nealleyi* Vasey), Palmer amaranth, and hemp sesbania were planted in six-cell trays filled with commercial potting soil-mix

(LC1 Potting Mix, Sungro Horticulture Inc., Agawam, MA, USA) and maintained in a greenhouse at a day/night temperature regime of 35/25° C, with a 12-hr photoperiod. Conversely, five rice (Presidio variety) seeds were planted in 10 cm diameter pots filled with the same potting media. For the corn gluten meal evaluation, an autoclaved field soil was used.

Herbicide screening. Corn gluten meal was applied at 2 g dm^{-2} (Baker and Grant 2018), incorporated in the soil prior to planting the rice and weed seed at 14 days after planting (DAP). Non-synthetic herbicides were applied at 14 DAP of grass and broadleaf weed species. A research track sprayer fitted with a flat fan nozzle (TeeJet XR110015) calibrated to deliver 140 L ha^{-1} of spray volume at 276 kPa pressure, at an operating speed of 4.8 km h^{-1} was used in herbicide application. Visual injury was documented at 3, 14, and 21 days after application (DAA) of herbicide using a scale of 0-100% (0% = no injury and 100% = plant death). Aboveground biomass was collected for rice and weeds at 21 DAA.

Statistical analysis. Analysis of variance **(**ANOVA) for herbicide screening was carried out using JMP Pro version 14 (SAS Institute Inc., Cary NC, USA) to determine treatment by run interactions. Treatment by run interactions were not significant and thus the data were pooled across the two experimental runs for final analysis, using ANOVA for the herbicide screening and aboveground biomass data. Means were separated using Tukey's Honestly Significant Difference HSD (α=0.05).

Field experiment. A field experiment was conducted in two different locations at Eagle Lake, TX to evaluate the performance of the non-synthetic herbicides to rice and weeds.

The two site locations were at the Bryan Wiese farm and the David Wintermann Rice Research Station conducted during 2017 and 2018, respectively.

Bryan Wiese farm site and experimental design. The Bryan Wiese farm was a certified organic farm located at Eagle Lake Texas (29° 32' 49.8588" N; 96° 15' 1.8828" W). The local farmer's practice was done in crop establishment. Jazzman, a long grain rice variety, was planted using a drill planter at 7 cm row spacing (Sha et al. 2011). Plot size was 6 m × 4 m (length × width). Since the field was organic-certified, All non-synthetic herbicides were used except for Homeplate® (Table 6). The treatments were arranged in a randomized complete block design with four replications. A nontreated control (weedy check) and hand-weeded (weed-free) plots were included for yield and injury comparison. Hand-weeding was done at 7, 14, 21, and 28 DAP. Mechanical weeding was done using an implement pulled behind a tractor at 7 and 21 DAP. Non-synthetic herbicides were applied using a back-pack sprayer using a four nozzle boom spaced 51 cm apart delivering 280 L ha^{-1} at 276 kPa. Flat fan nozzles (TeeJet XR110015) were used in herbicide application. Postermergence (EPOST) application of herbicides were made at 5 to 8 cm weed height (20 DAP) initial vegetative stage of the crop. Visual rice injury was documented at 7, 14, and 21 DAA of herbicide using a scale of 0-100% (0% = no injury and 100% = plant death). Overall weed control was recorded at the same timings using a scale of 0-100% (0% = not controlled and 100% = weed-free).

Rice yield was hand-harvested in three randomly placed quadrats (1 m^2) from each plot and grain moisture was adjusted at 12%. Yield was calculated on a kilogram per hectare basis.

David Wintermann Rice Research Station site and experimental design. The David Wintermann Rice Research (29° 37' 9.8652" N; 96° 21' 46.8504" W) is a research station for conventional rice production. Presidio rice variety (McClung 2005) was planted using a drill-seed planter with 15 cm row spacing. Plot sizes were 5 m × 1.5 m. A weedy and a weed-free (hand-weeded) check were included. Weedy check plots were used to compare in weediness of the plots. Non-synthetic herbicides were applied using a back-pack sprayer using a four nozzle boom spaced 51 cm apart delivering 280 L ha^{-1} at 276 kPa. Flat fan nozzles (TeeJet XR110015) were used in herbicide application. Early postemergence (EPOST) and mid-postemergence (MPOST) herbicide applications were done at 14 and 21 DAP, respectively. Visual rice injury was documented at 3, 14, and 21 DAA of herbicide using a scale of 0-100% (0% = no injury and 100% = plant death). Overall weed control was recorded at the same timings using a scale of 0-100% (0% = not controlled and 100% = weed-free). Rice yield was mechanically harvested using a small plot combine and grain moisture was adjusted to 12%. Yield was calculated on a kilogram per hectare basis.

Statistical analyses. Analysis of variance **(**ANOVA) for crop and weed herbicide response data was carried out using JMP Pro version 14 (SAS Institute Inc., Cary NC, USA) to determine location by year interactions. Location by year interactions were significant and thus the data were analyzed separately for the two experimental runs for final analysis, using ANOVA. Means were separated using Tukey's Honestly Significant Difference HSD (α=0.05).

Results

All non-synthetic herbicides were used in the greenhouse experiment except Homeplate (caprylic+capric acid) for weeds. The greenhouse experiment was conducted to assess preliminary evaluation of non-synthetic herbicides to weeds. Yellow nutsedge (*Cyperus esculentus* L.) injury was negligible when non-synthetic herbicides are applied as EPOST. Sustane (corn gluten meal) applied preemergence caused little or no injury to weed species tested in the greenhouse experiment. Weed biomass reduction relative to the non-treated check at 21 DAA was minimal in Sustane treatments. Furthermore, all non-synthetic herbicides caused neglible injury to weeds at 21 DAA of EPOST (Figure 13 and 14). The on-farm experiment was conducted using organic management practices compared to the on-station experiment where plant culture was initially established using conventional rice methods. The on-station study had both EPOST and MPOST applications. EPOST application was done for the on-farm experiment. All non-synthetic herbicides listed in Table 1 were evaluated in the field experiments.

Weed control in greenhouse experiments at 3 DAA. Broadleaf weeds had different response to non-synthetic herbicides 3 days after application (DAA) (Figure 13). BurnOut (citric acid+clove oil) caused 84% injury to morningglory applied at early postemergence (Figure 13). Morningglory was also controlled by EPOST application of Avenger (citrus oil) (74%) and Suppress (caprylic, capric acid) (75%). Diluted vinegar (acetic acid) solutions (20% and 30%) caused 55 to 63% injury to morningglory.

WeedZap (clove oil+cinnamon oil) and Alldown (clove oil+acetic acid) caused 43% injury to morningglory. Suppress caused 67% injury to Palmer amaranth. Vinegar solutions caused 5% injury to Palmer amaranth. Hemp sesbania was most sensitive to BurnOut applied EPOST (31%). EPOST application of Avenger, Suppress and BurnOut caused 16 to 20% to hemp sesbania. Suppress was the most injurious herbicide to the grassy weeds species in the greenhouse study. Suppress applied EPOST caused 48%, 81%, 60% injury to broadleaf signalgrass, large crabgrass, and barnyardgrass at 3 DAA, respectively (Figure 14). BurnOut and Alldown caused 21% and 20% injury to barnyardgrass, respectively. Alldown caused 28% injury to broadleaf signalgrass at 3 DAA of EPOST.

Weed control in greenhouse experiments at 14 and 21 DAA. Avenger, BurnOut, and Suppress caused 25 to 26% injury to ivyleaf morningglory at 14 DAA of EPOST. Suppress caused 36% and 26% injury to Palmer amaranth and hemp sesbania at 14 DAA, respectively (Figure 13). Avenger, BurnOut, and Suppress caused 25% injury to ivyleaf morningglory at 21 DAA (Figure 13). Large crabgrass and barnyardgrass injury were 35% and 25% at 14 DAA of Suppress (Figure 14). Minimal injury to the grassy species was recorded across all treatments at 21 DAA (Figure 14).

Relative biomass in greenhouse experiments at 21 DAA. BurnOut reduced the biomass of ivyleaf morningglory and hemp sesbania by 52%and 58%, respectively (Figure 13). Alldown, Avenger, BurnOut, and Suppress reduced Palmer amaranth biomass by 20-31%. Weedzap reduced the ivyleaf morningglory, Palmer amaranth, and hemp sesbania by 39%, 10%, and 16%, respectively. Suppress reduced broadleaf signalgrass, large crabgrass, and barnyardgrass biomass by 50%, 32%, 55%, respectively (Figure 14). Diluted vinegar solutions did not reduce the biomass of broadleaf signalgrass and large crabgrass at 21 DAA. Alldown and BurnOut reduced barnyardgrass biomass by 41%. Diluted vinegar (30%) reduced barnyardgrass biomass by 20%.

Rice injury in greenhouse experiments at 3, 14, 21 DAA. Rice was very sensitive to the non-synthetic herbicides applied at EPOST. Homeplate caused 90% injury to rice. BurnOut and Vinegar (30%) caused 78% injury to rice evaluated 3 DAA EPOST. Corn gluten applied PPI and EPOST caused 27% and 22% injury to rice (Table 7). At 14 DAA of EPOST, Homeplate, Suppress, and the diluted vinegar solutions caused 68% to 78% injury to rice. BurnOut and Alldown caused 46% and 40% injury to rice at 21 DAA, respectively. Vinegar (30%) and Homeplate caused 39% injury to rice at 21 days. At 21 DAA, all foliar applied non-synthetic herbicides reduced rice biomass by 59 to 76% relative to the non-treated check. Sustane applied PPI and EPOST caused 21 to 24% biomass reduction at 21 DAA.

On-station research experiment. At 3 DAA of EPOST, Homeplate and Suppress 86% to 93% and 80% injury to broadleaf signalgrass and barnyardgrass (Figure 15). Avenger caused 70% control to broadleaf signalgrass at 3 DAA. Vinegar (30%) controlled 70% of the barnyardgrass in the field. BurnOut, Homplate, Suppress, WeedZap, and diluted vinegar solutions caused 60 to 90% injury to ivyleaf mroningglory. Homeplate caused 87% control to hemp sesbania. Homeplate provided the overall best weed control (90%) among the herbicides tested after hand weeding. At

3 DAA of MPOST, Homeplate caused 86% control to barnyardgrass (Figure 16). MPOST application of Homeplate caused 51% control to broadleaf signalgrass. Broadleaf species were much more sensitive to MPOST application of non-synthetic herbicides. Homeplate caused 88% and 82% control to ivyleaf morningglory and hemp sesbania, respectively (Figure 16).

Hand weeding provided the best overall weed control (100%) at 3 DAA (Table 8). Homplate caused 90%, 83%, and 71% overall weed control at 3, 14, and 21 DAA. MPOST application of Homeplate controlled weeds by 88%, 78%, and 41% at 3, 14, and 21 DAA, respectively.

On-farm research experiment. Overall weed control was recorded for the on-farm experiment. Species-wise weed control was not evaluated since the field was infested with broadleaf signalgrass and barnyardgrass. Suppress provided 64, 54, and 44% weed control at 3, 14, 21 DAA. Excellent weed control (100%) from hand weeded plots was recorded from the three evaluation period. Sustane applied PPI and EPOST caused 17 to 19% overall weed control and only 5% weed control at 3 DAA and 21 DAA, respectively (Table 9).

Rice injury and rice yield on-farm experiment. Sustane caused 46%, 38%, and 18% injury to rice at 3, 14, and 21 DAA, respectively. Sustane PPI and Alldown caused 36% rice injury at 3 DAA. Vinegar (30%) caused 28% injury to rice(Table 4). Avenger WeedZap, and Sustane EPOST did not injure rice at 21 DAA. Hand-weeded plots provided the best yield in the on-farm experiment (3500 kg ha^{-1}) (Table 9). All treatments yielded 1640 to 2880 kg ha^{-1}.

Rice injury and rice yield on-station experiment. EPOST application of Homeplate caused 77% and 46% injury to rice at 3 and 14 DAA, respectively. Alldown and Vinegar dilutions caused 45 to 48% injury to rice at 3 DAA (Table 10). At 21 DAA, all weed control treatments did not injure rice. MPOST application of Homeplate and Suppress caused 80 to 81% injury to rice at 3 DAA (Table 5). BurnOut and Vinegar (30%) caused 61 to 69% injury at 3 DAA. At 14 DAA, Homeplate caused 54% injury to rice followed by Suppress (46%). Sustane applications caused 15 to 20% injury to rice. No injury was seen to all treatments at 21 DAA. Plots treated with Homeplate at EPOST and MPOST yielded 7580 and 7230 kg ha^{-1}, respectively (Table 5). Hand-weeding done at MPOST had the yielded 7730 kg ha^{-1}.

Discussion

Non-synthetic herbicides have very little crop selectivity (Dayan et al. 2009). Mostly leaf burn injury are the symptoms seen in rice leaf surface when non-synthetic herbicides are applied in controlled and natural environments (Figure 5). For example, Homeplate symptomology in rice shows water-soaked lesions in the leaf surface gradually leading to leaf burning over time is observed (Figure 6). However, our rice plants recovered at 21 DAA of herbicide regardless both in our greenhouse and field experiments. Although non-synthetic herbicides caused significant rice injury at the early stages, the crop was able to recover without negatively impacting the yield. The ability of rice to withstand injury to non-synthetic herbicide is similar to the process of propanil metabolism. Although limited to no research has been done in the injury of non-synthetic herbicides to rice, propanil could be the closest herbicide that has similar effect to rice (Hodgson 1971). Environmental factors could also play in the level of toxicity of non-synthetic herbicides in rice such as temperature and daylength (Hodgson 1971). Non-synthetic herbicides applied posteemergence to rice can have similar response to propanil (Smith Jr 1974). Although our study could not address the exact mechanism of action how rice is able to withstand the injury caused by non-synthetic herbicides, we could get an idea on how these compounds could be metabolize by conducting more in-depth laboratory assays.

Since most of non-synthetic herbicides are broad-spectrum, field and greenhouse experiments showed high injury to rice at 3 DAA. Our greenhouse and on-farm experiment showed lower crop injury and weed control compared to the on-station experiment due to a lower spray volume. Herbicide efficacy can vary depending on the spray volume (Knoche 1994). Ramsdale and Messersmith (2001) reports the efficacy of herbicide such as carfentrazone could be reduced if spray volume is also reduced from 190 L ha^{-1} to 47 L ha^{-1}. Knoche (1994) reports that 44% of the experiments conducted resulted into decreased efficacy as a result of reduced spray volume. Non-synthetic herbicides, mostly contact, would have more pronounced weed efficacy if applied at higher spray volumes (Borger et al. 2013). Homeplate (caprylic+capric acid) provided better weed control in the on-research site due to a higher spray volume application. Thus, better efficacy and symptoms could be seen in leaf surface of the weeds (Figure 6). Acetic acid concentrations have better efficacy when applied at EPOST. Abouziena et al. (2009) reported that annual grasses were controlled at least 79% when applied at a younger stage. Alldown (citric acid+clove oil) performs better applied EPOST compared to MPOST in our study and was similar to the reports of Abouziena et al. (2009). Delayed application of Alldown can decrease the efficacy of weed control to some broadleaf reducing herbicide performance up to 67%. Our corn gluten meal applications were better applied at PPI compared to EPOST. Our results were in harmony with Abouziena et al (2009) where corn gluten applied at early stage controlled 80 to 90% of broadleaf weed species evaluated at one week after treatment. Therefore, better corn gluten meal efficacy could be achieved if applied as a preemergence herbicide.

Conclusion

Palmer amaranth, hemp sesbania, ivyleaf morningglory, barnyardgrass, broadleaf signalgrass, and large crabgrass had different responses to non-synthetic herbicides. Increasing the spray volume of non-synthetic herbicides increases the efficacy of weed control. Corn gluten meal applied as premergence has low weed control efficacy. Morningglory and hemp sesbania were more susceptible to clove oil+citric acid while Palmer amaranth and grass weeds wernjured by caprylic+capric acid. Alldown and BurnOut used in this study control broadleaf weed species such as ivyleaf morningglory and Palmer amaranth applied as early postemergence. Homeplate provided the best weed control among the herbicides tested. Majority of research has been conducted in organic fruit and vegetable production using non-synthetic herbicides and rice response to these herbicides are limited or not known. The efficacy and tolerance of non-synthetic herbicides vary depending on the weed height and the stages of rice. Relatively few organic rice producers use non-synthetic herbicides in organic rice production systems due to lack of information of rice tolerance and weed efficacy. Therefore, further field tests in different rice stages and varying spray application volume is needed to supplement information in rice tolerance and efficacy in weed control of non-synthetic herbicides to support the growing organic rice industry in the US. Non-synthetic herbicides provide organic rice growers in Texas additional option to control weeds and can be integrated into a portfolio of existing weed control tools in an organic system along with the use of allelopathic/weed suppressive rice varieties and flooding depth management.

References

Abouziena HFH, Omar AAM, Sharma SD, Singh M (2009) Efficacy comparison of some new natural-product herbicides for weed control at two growth stages. Weed Technol. 23:431-437

Arnhold S, Lindner S, Lee B, Martin E, Kettering J, Nguyen TT, Koellner T, Ok YS, Huwe B (2014) Conventional and organic farming: Soil erosion and conservation potential for row crop cultivation. Geoderma 219:89-105

Bagavathiannan MV, Norsworthy JK (2012) Late-season seed production in arable weed communities: management implications. Weed Sci. 60:325-334

Baker BP, Grant JA (2018) Active Ingredients Eligible for Minimum Risk Pesticide Use: Overview of the Profiles. Cornell Cooperative Extension. https://ecommons.cornell.edu/xmlui/bitstream/handle/1813/52630/overview-profiles-NYSIPM.pdf?sequence=2. Accessed: October 30, 2019

Baker BP, Grant JA (2018) Citric acid profile. Cornell Cooperative Extension. https://ecommons.cornell.edu/bitstream/handle/1813/56118/citric-acid-MRP-NYSIPM.pdf?sequence=1 Accessed: October 29, 2019

Baker BP, Grant JA (2018) Corn gluten meal profile. Active ingredient eligible for minimum risk use pesticide use. New York State Integrated Pest Management. Cornell University. NY: Geneva

Baker BP, Grant JA (2018). Cinnamon and cinnamon oil profile: active ingredient eligible for minimum risk pesticide use. Cornell Cooperative Extension.

https://ecommons.cornell.edu/bitstream/handle/1813/56117/cinnamon-MRP-NYSIPM.pdf?sequence=1 Accessed: October 28, 2019

Baker BP, Grant JA (2018). Corn gluten meal profile: active ingredient eligible for minimum risk pesticide use. Cornell Cooperative Extension. https://ecommons.cornell.edu/bitstream/handle/1813/56121/corn-gluten-meal-MRP- NYSIPM.pdf?sequence=1. Accessed: October 28, 2019.

Baker BP, Grant JA, Malakar-Kuenen (2018) Cloves and clove oil profile: active ingredient eligible for minimum risk pesticide use. Cornell Cooperative Extension. https://ecommons.cornell.edu/bitstream/handle/1813/56120/clove-oil-MRP- NYSIPM.pdf?sequence=1&isAllowed=y. Accessed October 29, 2019

Bergeron EA, Webster EP, McKnight BM, Rustom SY Jr (2015) Evaluation of herbicides for Nealley's sprangletop (*Leptochloa nealleyi*) control http://www.cbai2015.com.br/docs/trab-2-6875-365.pdf. Accessed: November 1, 2019

Bond W, Grundy AC (2001) Non-chemical weed management in organic farming systems. Weed Res. 41:383-405

Borger CD, Riethmuller GP, Ashworth M, Minkey D, Hashem A, Powles SB (2013) Increased carrier volume improves preemergence control of rigid ryegrass (Lolium rigidum) in zero-tillage seeding systems. Weed Technol. 27:649-655

Chappell L, Knox G, Stamps RH (2012) Alternatives to synthetic herbicides for weed management in container nurseries. University of Georgia Cooperative Extension Bulletin 1410

Coleman, Robert, and Donald Penner (2008) Organic acid enhancement of pelargonic acid. Weed Technol. 22:38-41

Dayan FE, Cantrell CL, Duke SO (2009) Natural products in crop protection. Bioorg. Med. Chem. 12:4022-4034

Dayan FE, Owens DK, Duke SO (2012) Rationale for a natural products approach to herbicide discovery. Pest Manage. 68:519-528

Diver SL, Adam KL (2008) Sustainable small-scale nursery production. ATTRA. 28pp https://attra.ncat.org/product/sustainable-small-scale-nursery-production/ Accessed October 15, 2019

Evans GJ, Bellinder RR (2009) The potential use of vinegar and a clove oil herbicide for weed control in sweet corn, potato, and onion. Weed Technol. 23:120-128

Gunderson JJ, Carr PM, Winch T (2008) An Efficacy Trial of Potential Herbicides for Use in Organic Systems. North Dakota State University, Dickinson Research Extension Center

Hodgson RH (1971) Influence of environment on metabolism of propanil in rice. Weed Sci. 19:501-507.

Hsu, H.J., S. Trusovs, and F.R. Fernandez. 2012. Organic herbicide. US Patent Office 8,188,004, issued May 2012. https://www.google.com/patents/US8188004

IFOAM (2016) The world of organic agriculture: statistics and emerging trends. Accessed March 22, 2018. http://orgprints.org/31151/1/willer-lernoud-2016-world-of-organic.pdf

Knoche M (1994) Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Prot. 3:163-178

Kong CH, Hu F, Peng W, Wu JL (2008) Effect of allelopathic rice varieties combined with cultural management options on paddy field weeds. Pest Manag. Sci. 64:276-282

Kwon JA, Yu CB, Park HD (2003) Bacteriocidal effects and inhibition of cell separation of cinnamic aldehyde on *Bacillus cereus*. Lett. Appl. Microbiol. 37:61-65

Liebman M, Davis AS, Francis C (2009) Managing weeds in organic farming systems: an ecological approach. Organic farming: the ecological system. Agron. Monogr. 54:173-195

Liu, Rui (2018). Survey, Ecology and Management of Problematic Weeds in Rice Production in Texas. Doctoral dissertation, Texas A & M University. Available electronically from http://hdl.handle.net/1969.1/174367

McClung AM (2005) Presidio rice: a new long grain rice with improved ratoon crop potential and milling yield. Texas Rice 5:11

Norsworthy JK, Bond J, Scott RC (2013) Weed management practices and needs in Arkansas and Mississippi rice. Weed Technol. 27: 623-630

Oerke EC, Dehne HW (2004) Safeguarding production-losses in major crops and the role of crop protection. Crop Prot. 23:275-285

Organic Materials Review Institute. 2019. Who we are. https://www.omri.org/about (Accessed October 15, 2019)

Pachlatko JP (1998) Natural products in crop protection. Chimia 52:29–47

Ramsdale BK, Messersmith CG (2001) Nozzle, spray volume, and adjuvant effects on carfentrazone and imazamox efficacy. Weed Technol. 15:485-491

Raynolds L (2000) Re-embedding global agriculture: The international organic and fair trade movements. Agric. Hum. Val. 17:297-309

Riar DS, Norsworthy JK (2011) Use of imazosulfuron in herbicide programs for drill-seeded rice (*Oryza sativa*) in the mid-South United States. Weed Technol. 25:548-555

Santos JER, Villarino BJ, Zosa AR, Dayrit FM (2011). Analysis of volatile organic compounds in virgin coconut oil and their sensory attributes. Philippine J. Sci. 140:161-171.

Sha X, Linscombe S, Jodari F, Chu Q, QR, Groth DE, Blanche SB, Harell DL, White LM, Oard JH, Chen MH, Theunissen SJ (2011) Registration of Jazzman aromatic long grain rice. J. Pl. Reg. 5:304-308

Smith Jr RJ (1974) Responses of rice to postemergence treatments of propanil. Weed Sci. 22:563-568

Texas Department of Agriculture (2019). Regulatory programs: organics. https://www.texasagriculture.gov/RegulatoryPrograms/Organics.aspx. Accessed: November 1, 2019

United States Department of Agriculture (2019) USDA Organic. https://www.usda.gov/topics/organic. Accessed November 1, 2019

United States Government (1990) Organic Foods Production Act. Available at: https://www.ams.usda.gov/sites/default/files/media/Organic%20Foods%20Production%20Act%20of%201990%20(OFPA).pdf. Accessed: November 1, 2019

Wendakoon CN, Sakaguchi M (1995) Inhibition of amino acid decarboxylase activity of Enterobacter aerogenes by active components in spices. J. Food Prod. 58:280-283

Williams PR, Hammitt JK (2001) Perceived risks of conventional and organic produce: pesticides, pathogens, and natural toxins. Risk Analysis 21:319-330

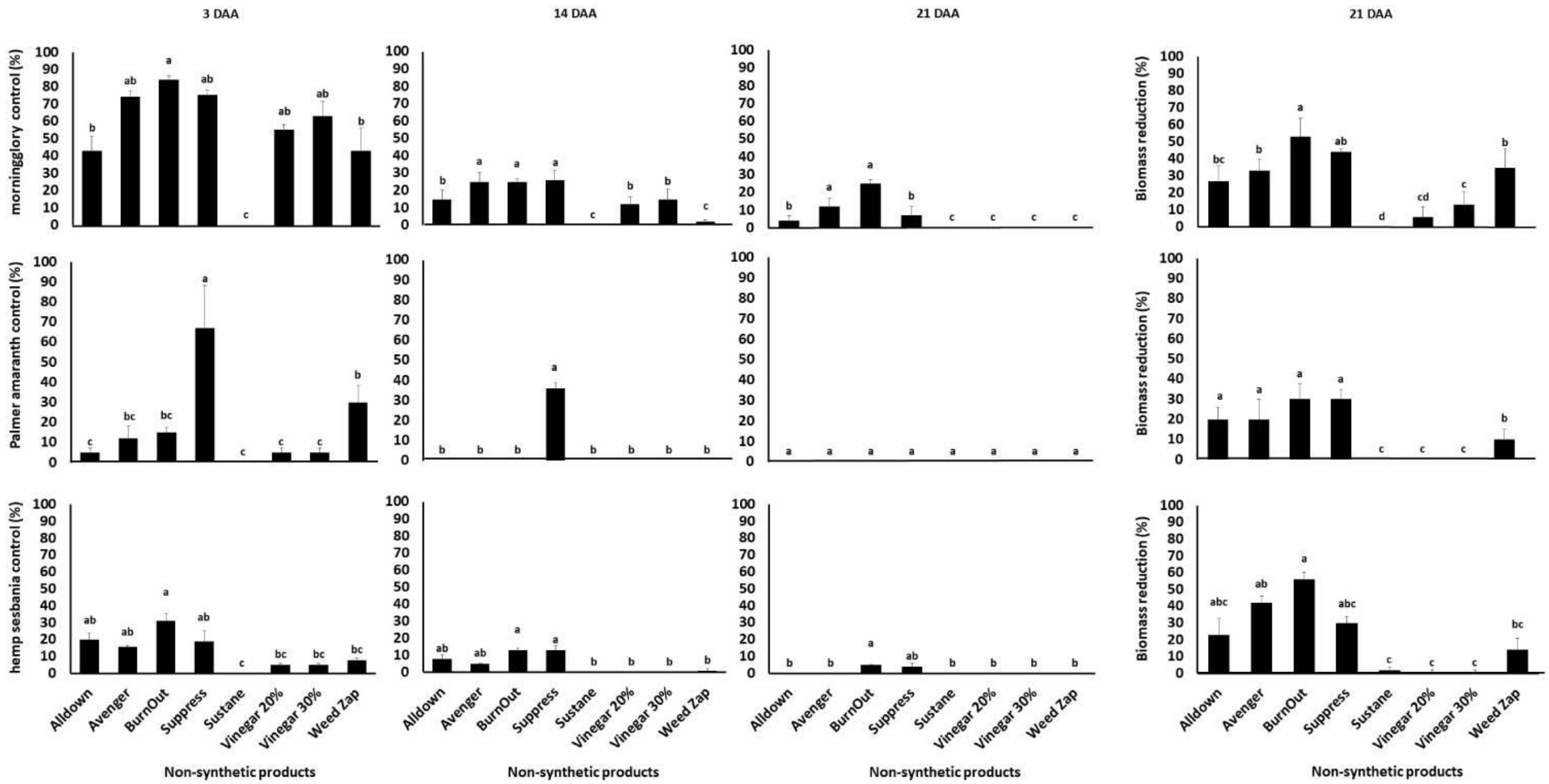


Figure 13. Injury on broadleaf weeds caused by different non-synthetic herbicides at 3, 14 and 21 days after application (DAA), and relative biomass reduction (compared to non-treated check) at 21 DAA in a greenhouse experiment at College Station, TX. Sustane was applied as preplant incorporation, whereas all other herbicides were applied as foliar application.

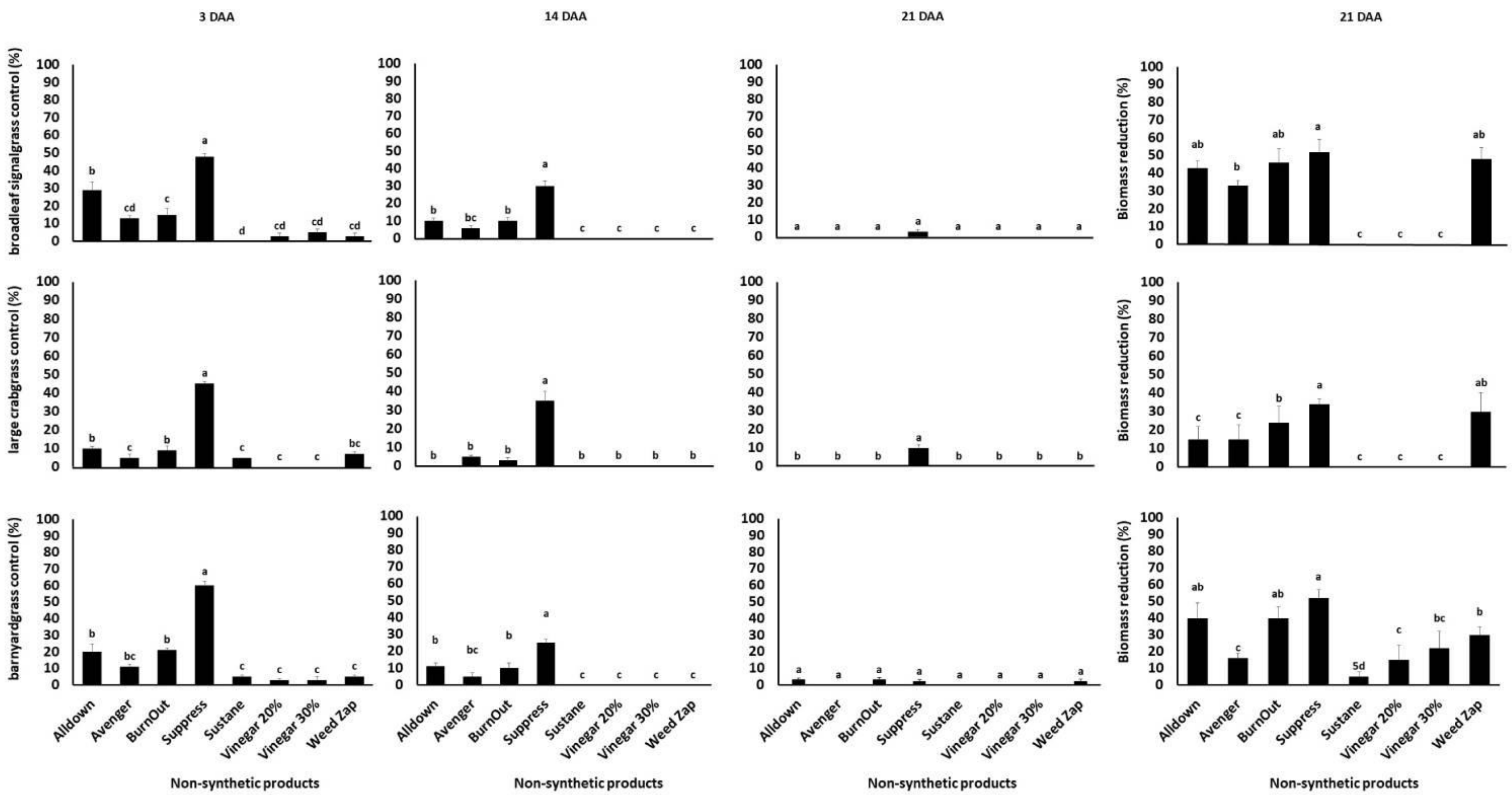


Figure 14. Injury on grass weeds caused by different non-synthetic herbicides at 3, 14 and 21 days after application (DAA), and relative biomass reduction (compared to a non-treated check) at 21 DAA in a greenhouse experiment at College Station, TX. Sustane was applied as preplant incorporation, whereas all other herbicides were applied as foliar application.

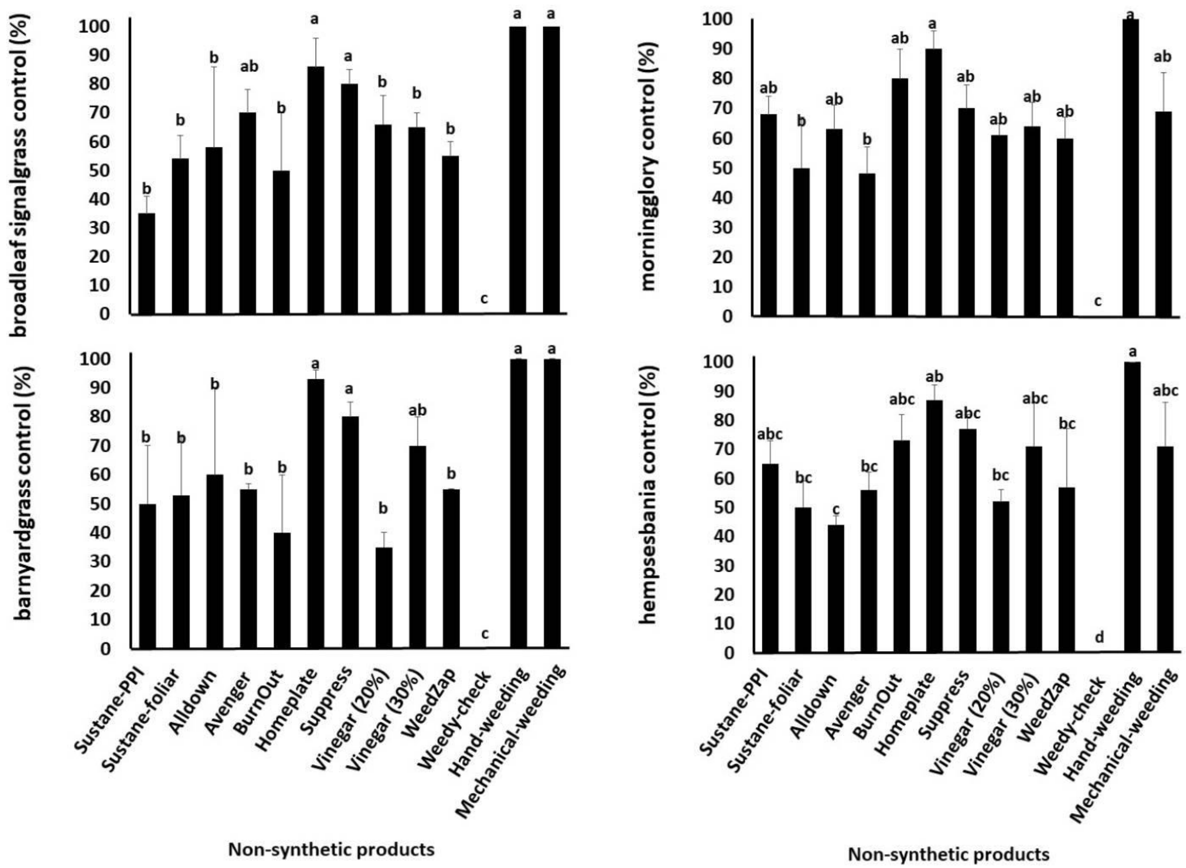


Figure 15. Weed control efficacy (3 days after application) of various non-synthetic products applied EPOST (14 days after rice planting) in the on-station research experiment in 2019. Hand weeding was carried out at 7, 14, 21, and 28 days after rice planting; mechanical weeding was carried out at 7 and 21 days after planting; Sustane-PPI indicates preplant incorporation.

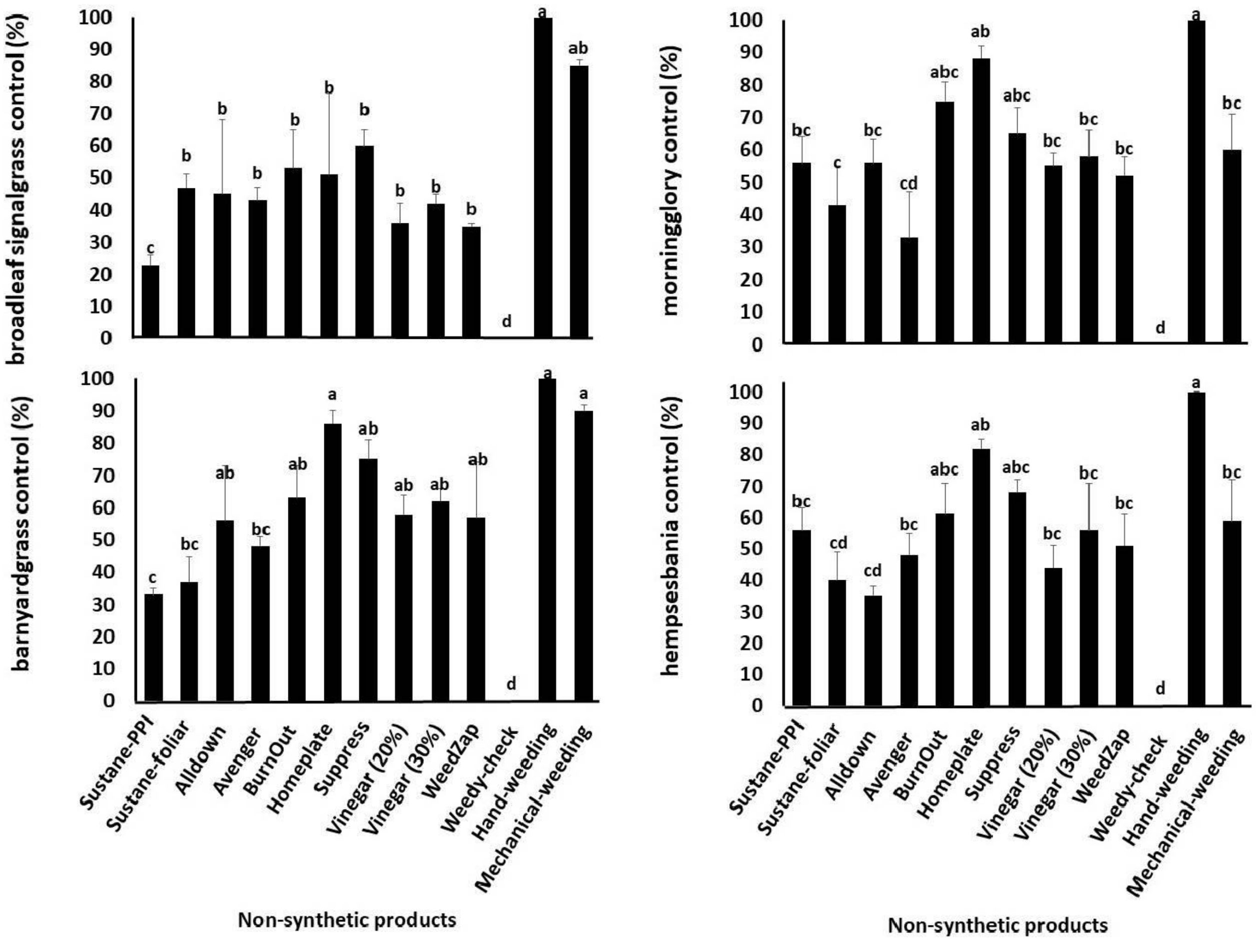


Figure 16. Weed control efficacy (3 days after application) of various non-synthetic products applied MPOST (28 days after rice planting) in the on-station research experiment in 2019. Hand weeding was carried out at 7, 14, 21, and 28 days after rice planting; mechanical weeding was carried out at 7 and 21 days after planting; Sustane-PPI indicates preplant incorporation.

Figure 17. Rice injury at 3 DAA EPOST of A) Alldown, B) Vinegar (20%), C) Vinegar (30%), D) Avenger, E) BurnOut, F) Avenger, G) Homeplate, H) Suppress, I) WeedZap in greenhouse environment.

Figure 18. Homeplate (caprylic acid+capric acid) injury to broadleaf signalgrass (*Urochloa platyphylla* L.) and rice (*Oryza sativa* L.) applied at EPOST in the field after an hour.

Table 6. List of non-synthetic products used in the greenhouse and field experiments

Trt. No.	Trade name	Active ingredient	Time of application[a]	Rate[b] ml L^{-1}	Product in solution (%)	OMRI[c] certified	Manufacturer name	Manufacturer Address	Source
1	Sustane	Corn gluten	PPI	100	10	YES	Sustane Natural Fertilizer, Inc.	Cannon Falls, MN	www.sustane.com
2	Sustane	Corn gluten	EPOST	100	10	YES	Sustane Natural Fertilizer, Inc	Cannon Falls, MN	www.sustane.com
3	Alldown	Acetic acid+ clove oil	EPOST; MPOST	500	50	YES	Summerset	Chaska, MN	www.summersetproducts. com
4	Avenger	Citrus oil	EPOST; MPOST	199	20	YES	Avenger Products, LLC	Gainesville, GA	www.avengerorganics.com
5	BurnOut	Clove oil+ citric acid	EPOST; MPOST	332	33	NO	Bonide Products, Inc.	Oriskany, NY	www.bonide.com
6	Homeplate	Caprylic acid; capric acid	EPOST; MPOST	50	5	YES	Certis USA	Columbia, MD	www.certisusa.com
7	Suppress	Caprylic acid; capric acid	EPOST; MPOST	50	5	YES	Westbridge Agricultural Products	Vista, CA	www.westbridge .com
8	Vinegar (20%)	Acetic acid	EPOST; MPOST	500	50	YES	EcoClean Solutions Inc.	Copaigue, NY	www.greengobbler. com
9	Vinegar (30%)	Acetic acid	EPOST; MPOST	500	50	YES	EcoClean Solutions Inc.	Copaigue, NY	www.greengobbler. com
10	WeedZap	Clove oil+ cinnamon oil	EPOST; MPOST	50	5	YES	Safergro Laboratories	Ventura, CA	www.safergro.com

[a]Abbreviations: PPI, preplant incorporated; EPOST, early postemergence; MPOST, mid postemergence

[b]Corn gluten meal was applied in g m^{-2}. All other herbicides were applied in ml L^{-1} (V/V).

[c]Organic Materials Review Institute

Table 7. Rice injury (3, 14 and 21 DAA) and biomass (21 DAA) in response to various non-synthetic herbicide products applied in the greenhouse experiment[a]

Herbicide	Active ingredient	Application timing[b]	Crop injury						Rice biomass reduction[c]	
			3 DAA		14 DAA		21 DAA			
			%		%		%		%	
Sustane	Corn gluten	PPI	27	(3.2) d	17	(2.6) d	5	(1.7) d	24	(5.5) b
Sustane	Corn gluten	EPOST	22	(2.0) d	9	(2.0) d	3	(1.8) d	21	(6.7) b
Alldown	Acetic acid+clove oil	EPOST	72	(3.0) bc	53	(3.1) bc	40	(3.0) a	60	(4.4) a
Avenger	Citrus oil	EPOST	70	(3.9) bc	50	(3.2) c	27	(1.8) c	59	(0.9) a
BurnOut	Clove oil+citric acid	EPOST	78	(4.2) abc	65	(3.7) ab	46	(2.4) a	67	(5.6) a
Homeplate	Caprylic acid; capric acid	EPOST	90	(1.8) a	78	(3.5) a	39	(2.3) a	76	(1.1) a
Suppress	Caprylic acid; capric acid	EPOST	83	(1.9) ab	73	(2.2) a	38	(2.1) ab	65	(2.1) a
Vinegar (20%)	Acetic acid	EPOST	75	(3.2) bc	68	(2.6) a	40	(1.9) a	67	(1.7) a
Vinegar (30%)	Acetic acid	EPOST	78	(0.9) abc	70	(1.7) a	39	(3.4) a	77	(1.5) a
WeedZap	Clove oil+cinnamon oil	EPOST	68	(1.8) c	51	(3.1) c	28	(1.6) bc	68	(1.9) a

[a]Abbreviation: DAA, days after application; Data collected from greenhouse; Means were separated using Tukey's Honestly Significant Difference ($\alpha = 0.05$).

[b]Abbreviation: PPI, preplant incorporated; EPOST, early postemergence

[c]Rice relative biomass was calculated based on non-treated check at 21 DAA

Table 8. Overall weed control at 3, 14 and 21 days after application of various non-synthetic herbicide products in the on-station experiment at the David Wintermann Rice Research Station, Eagle Lake, TX, 2019[a]

Herbicide[b]	**Active ingredient**	**Overall weed control**[c]					
		EPOST			**MPOST**		
		3 DAA	**14 DAA**	**21 DAA**	**3 DAA**	**14 DAA**	**21 DAA**
		%					
Sustane	Corn gluten	66 c	58 d	35 cd	63 c	61 bc	45 b
Sustane	Corn gluten	65 c	63 cd	41 d	64 c	61 bc	43 b
Alldown	Acetic acid+clove oil	64 c	66 bcd	51 bcd	65 c	56 bc	38 bc
Avenger	Citrus oil	65 c	58 d	50 bcd	64 c	53 c	40 b
BurnOut	Clove oil+citric acid	70 bc	60 d	46 cd	69 bc	65 bc	41 b
Homeplate	Caprylic acid; capric acid	90 ab	83 ab	71 b	88 ab	78 b	41 b
Suppress	Caprylic acid; capric acid	79 bc	80 bc	64 bc	81 abc	73 bc	50 b
Vinegar (20%)	Acetic acid	67 c	60 d	43 cd	68 bc	63 bc	46 b
Vinegar (30%)	Acetic acid	68 c	68 bcd	49 bcd	67 bc	66 bc	48 b
WeedZap	Clove oil+cinnamon oil	68 c	60 d	45 cd	63 c	71 bc	33 bc
Weedy check		0 d	0 e	0 e	0 d	0 d	0 c
Hand weeding		100 a	100 a	100 a	100 a	100 a	100 a
Mechanical weeding		72 bc	70 bcd	70 b	71 bc	76 b	88 a

[a]Means were separated using Tukey's Honest Significant Difference ($\alpha = 0.05$)a

[b]Hand weeding was conducted at 7, 14, 21, and 28 days after planting; mechanical weeding was done using a manual rotary weeder at 7 and 21 days after planting

[c]Abbreviations: EPOST, early postemergence applied at 14 days after rice planting; MPOST, mid postemergence applied at 28 days after planting; DAA, days after application

Table 9. Rice injury at 3, 14 and 21 days after application (DAA) of various non-synthetic herbicide products (EPOST timing) in the on-farm experiment, 2018[a]

Herbicide[b]	Active ingredient	Application timing[c]	Rice injury			Overall weed control[c]			Rice yield[d]
			3 DAA	14 DAA	21 DAA	3 DAA	14 DAA	21 DAA	
			--------------%-------------			--------------%-------------			kg ha^{-1}
Sustane	Corn gluten	PPI	36 (3.6) ab	31 (3.4) ab	11(3.6) ab	19 (0.8) f	6 (0.4) g	5 (0.6) de	1760 (0.52) ab
Sustane	Corn gluten	EPOST	16 (3.3) d	11 (3.2) de	0 (0.7) c	17 (2.5) f	8 (1.6) fg	5 (0.6) de	2080 (0.24) ab
Alldown	Acetic acid+clove oil	EPOST	36 (2.1) ab	31 (2.06) ab	11(1.9) ab	58 (5.0) bcd	48 (5.2) bcd	23 (1.2) c	2260 (0.52) ab
Avenger	Citrus oil	EPOST	21 (1.7) cd	16 (1.8) cd	0 (0.7) c	33 (5.5) ef	24 (5.3) ef	15 (3.4) cd	1640 (0.40) ab
BurnOut	Clove oil+citric acid	EPOST	28 (4.1) bcd	24 bcd (4.2)	6 (3.2) bc	41(3.9) de	31 (3.8) de	21 (3.2) c	1960 (0.55) ab
Suppress	Caprylic acid; capric acid	EPOST	46 (3.6) a	38 (3.4) a	18 (3.2) a	64 (2.7) b	54 (2.9) b	44 (3.4) b	2880 (0.11) ab
Vinegar (20%)	Acetic acid	EPOST	30 (1.6) bc	25 (1.7) bc	5 bc (2.0)	46 (3.8) cde	36 (3.9) cde	17 (2.5) c	1740 (0.28) ab
Vinegar (30%)	Acetic acid	EPOST	33 (1.6) bc	28 (1.5) abc	8 (1.3) bc	63 (3.5) bc	53 (3.5) bc	21 (1.5) c	1810 (0.40) ab
WeedZap	Clove oil+cinnamon oil	EPOST	16 (2.6) d	11 (2.7) de	0 (0.7) c	34 (3.7) ef	24 (3.5) ef	14 (4.3) cd	1970 (0.07) ab
Hand weeding			0 (1.0) e	0 (0.9) e	0(0.7) c	100 (0.7) a	100 (0.9) a	100 (0.6) a	3500 (0.54) a
Weedy check			0 (1.0) e	0 (0.9) e	0 (0.7) c	0 (0.7) g	0 (0.9) g	0 (0.7) e	960 b (0.56)
Mechanical weeding		EPOST	0 (1.0) e	0 (0.9) e	0 (0.7) c	100 (1.8) a	91 (0.4) a	93 (1.2) a	1760 (0.52) ab

[a]Means were separated using Tukey's Honestly Significant Difference ($\alpha = 0.05$).
[b]Hand weeding was carried out at 7, 14, 21, and 28 days after planting; Mechanical weeding was done using a tractor drawn implement scraping the top 2 cm of the soil at 7 and 21 days after planting.
[c]Abbreviations: PPI, preplant incorporated; EPOST, early postemergence applied at 14 days after planting. Broadleaf signalgrass and barnyardgrass were the dominant weed species on-farm.
[d]Grain yield was based on 12% adjusted moisture content.

Table 10. Rice injury at 3, 14 and 21 days after application (DAA) of various non-synthetic herbicide products (EPOST and MPOST timings) in the on-station experiment, 2019[a]

Herbicide[b]	**Active ingredient**	**Application timing**[c]	**Rice injury**			**Rice yield**[d]
			3 DAA	**14 DAA**	**21 DAA**	
			--------------------%--------------------			Kg ha^{-1}
Sustane	Corn gluten	PPI	24 (4.8) def	11 (1.8) def	0 a	6640 (0.25) ab
Sustane	Corn gluten	EPOST	21 (6.6) ef	10 (2.9) ef	0 a	6570(0.37) ab
Alldown	Acetic acid+clove oil	EPOST	46 (6.12) cd	24 (4.3) cd	0 a	6410(0.19) ab
Avenger	Citrus oil	EPOST	37 (1.8) cde	28 (3.3) bc	0 a	6490(0.23) ab
BurnOut	Clove oil+citric acid	EPOST	53 (6.07) bc	39 (1.4) ab	0 a	6940(0.28) ab
Homeplate	Caprylic acid; capric acid	EPOST	77 (3.4) a	46 (2.6) a	0 a	7580(0.24) a
Suppress	Caprylic acid; capric acid	EPOST	73 (3.5) ab	39 (2.6) ab	0 a	6600(0.18) ab
Vinegar (20%)	Acetic acid	EPOST	45 (5.13) cde	13 (2.5) def	0 a	6560(0.36) ab
Vinegar (30%)	Acetic acid	EPOST	48 (6.13) cd	26 (3.6) bc	0 a	6370(0.31) ab
WeedZap	Clove oil+cinnamon oil	EPOST	38 (5.4) cde	21 (1.9) cde	0 a	7070(0.11) ab
Hand weeding			0 (1.4) f	0 (1.2) f	0 a	7270(0.07) ab
Weedy check			0 (1.4) f	0 (1.2) f	0 a	6180(0.39) b
Mechanical			8 (3.4) f	0 (1.9) f	0 a	6790(0.17) ab
Sustane	Corn gluten	PPI*	21 (6.0) d	20 (3.3) d	0 a	6450(0.35) ab
Sustane	Corn gluten	MPOST	25 (4.1) d	15 (1.6) d	0 a	6480(0.37) ab
Alldown	Acetic acid+clove oil	MPOST	51 (6.3) c	24 (2.2) cd	0 a	6040(0.49) ab
Avenger	Citrus oil	MPOST	55 (3.8) bc	28 (2.0) cd	0 a	5740(0.56) ab
BurnOut	Clove oil+citric acid	MPOST	69 (4.7) abc	28 (3.9) cd	0 a	5820(0.56) ab
Homeplate	Caprylic acid; capric acid	MPOST	81 (3.2) a	54 (2.8) a	0 a	7230(0.25) a
Suppress	Caprylic acid; capric acid	MPOST	80 (3.3) ab	46 (2.3) ab	0 a	6370(0.18) ab
Vinegar (20%)	Acetic acid	MPOST	56 (6.6) abc	26 (2.7) cd	0 a	6300(0.58) ab
Vinegar (30%)	Acetic acid	MPOST	61 (6.2) abc	36 (3.7) bc	0 a	6030(0.50) ab
WeedZap	Clove oil+cinnamon oil	MPOST	58 (1.1) abc	28 (4.9 cd	0 a	6130(0.75) ab
Hand weeding			0 (3.4) d	0 (1.6) e	0 a	7730(0.56) a
Weedy check			0 (3.4) d	0 (1.6) e	0 a	4490(0.73) b
Mechanical			2.5 (5.8) d	15 (1.6) d	0 a	7550(0.28) a

[a]Means were separated using Tukey's Honestly Significant Difference ($\alpha = 0.05$).

[b]Hand weeding was carried out at 7, 14, 21, and 28 days after rice planting; mechanical weeding was done using a manual rotary weeder at 7 and 21 days after planting.

[c]Abbreviations: PPI, preplant incorporated; PPI*, preplant incorporated at the time of MPOST herbicide application; EPOST, early postemergence applied at 14 days after planting; MPOST, mid postemergence applied at 28 days after planting.

[d]Grain yield was based on 12% adjusted moisture content.

CHAPTER V

CONCLUSIONS

Overall, current research highlighted the importance of flooding, weed suppressive rice varieties, and non-synthetic herbicides as potential tools for weed control in organic rice. Effective flood management is necessary to control weeds especially in an environment where irrigation water is scarce. Flooding can be considered a potential non-chemical weed management tool in organic rice production in Texas. Rice varieties used in this study, namely PI 312777, PI 338046, and Jasmine 85 can suppress weed establishment and can be recommended for utilization in organic rice production. Although very limited information on yield response is documented for weed suppressive varieties in organic systems, these varieties can serve as a valuable tool for weed management in organic systems. Finally, non-synthetic herbicides can be used as an effective tool for weed control in organic rice production, either as a burndown or postemergence herbicide without impacting rice grain yield. Thus, flooding, weed suppressive varieties, and non-synthetic herbicides could be integrated as part of a robust weed management program in organic rice production.