Lecture in Honor of Former President Chia-Hua Chu: Building a Super Bright Protein Biochemistry for Submergence-tolerance Rice

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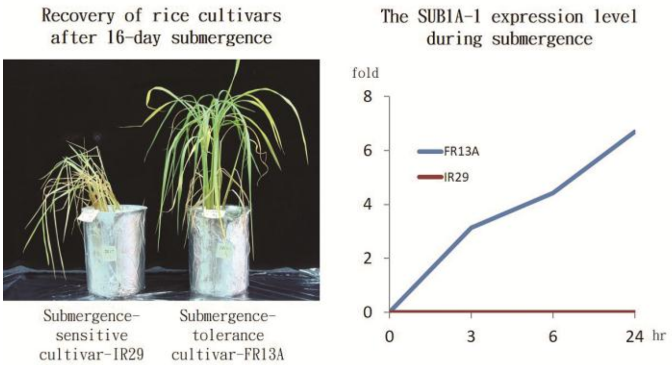
Abstract

The global food supply needs to increase by more than 60% within the next two decades in order to meet the needs predicted by global population growth projections. However, more natural disasters in agricultural areas pose a significant obstacle to this gain. Some wild rice cultivar possessing Sub1A-1 can survive up to 2 weeks of submergence. In collaboration of Dr. Ming-Che Shih, our recent studies suggest a new mechanism of Sub1A-1 in responses to submergence stress.



Food crisis and climate change

Whenever a typhoon approaches, we anticipate the weather service announcement and begin to look forward to a day off. While we wonder if we will get to rest at home, the typhoon may spell disaster for farmers. For example, Typhoon Meiji in 2015 devastated rice crops, with the cost reaching NT$110 million.

In addition to recovering from economic losses due to natural disasters, the global food supply needs to increase by more than 60% within the next two decades in order to meet the needs predicted by global population growth projections. However, climate change has greatly increased the possibility of flooding in agricultural areas, thus posing a significant obstacle to the 60% gain.

For the soaring Asian population, rice is one of our staple foods. Unlike other cereal crops, rice is a semiaquatic crop, so water is a major requirement for rice growth until it reaches the ripening stage. As a result, domesticated rice is often cultivated in the flooded paddy field of rainfed lowlands, river floodplains, or coastal deltas. The topography of the rice paddy field prevents fast water drainage. Therefore, unexpected heavy rainfall and poor water management of rice paddy fields can result in flooding of the aerial tissue (submergence), which puts rice under hypoxia stress that can lead to death. Rice can only produce two to three cycles of harvest a year, so any heavy rain could cause a large decline in rice crops, supplies, and profit that year.

Compared with domesticated rice, which is flood-sensitive, scientists have discovered wild flood-resistant rice cultivars and narrowed down the cause to the SUB1A-1 gene. This particular anti-submergence gene, SUB1A-1, inhibits rice growth during flooding to increase its survival overall (Figure 1). This is a similar strategy to how bears hibernate during winter. Our goal is to learn more about these wild rice cultivars. If we can understand how wild rice resists flood stress, we can improve the existing domesticated rice, and we might even discover other flood-resistant crops.

How Rice Detects Submergence

Before we can understand how SUB1A-1 helps rice resist flooding, we first ask how rice senses the flooding in the first place, or: how does rice detect submergence? Animals sense flooding by our eyes and noses. How does the plant know that it is being flooded and should therefore activate a submergence response? The flooding of the aerial tissue prevents oxygen exchange, thus putting the rice under hypoxia stress (no oxygen). Therefore, the oxygen level in the plant cells dramatically changes depending on the surrounding water level; normal water levels mean aerobic cellular conditions, while flooding means anaerobic cellular conditions. When oxygen levels change in the cell, a family of plant proteins (group seven ethylene response factor, or ERF-VII) will respond accordingly.

The ERF-VII proteins are transcription factors that act like a switch to initiate the manufacturing of in the cell. This protein family has a unique degradation motif called the N-degron, which is a unique amino acid sequence whose properties change upon oxidation (when the plant enters aerobic conditions). This change is a sign for the protein to be recognized by the r ubiquitin-proteasome system (UPS), which comes along to degrade the protein. Therefore, in aerobic conditions, the ERF-VII proteins are degraded as soon as they are made, so they cannot function in the cell. In the absence of oxygen (submergence), the ERF-VII proteins are not degraded, so they activate flood-resistence responses. In the case of rice, SUB1A-1 allows rice to enter a state similar to hibernation in order to survive flooding.

Unique features of SUB1A-1

As a member of the ERF-VII family, the rice protein SUB1A-1 is the determining factor for flood resistance. Rice possessing SUB1A-1 will have greatly increased survival during submergence. Like other ERF-VIIs, SUB1A-1 has the characteristic N-degron amino acid sequence. Hence, we expect SUB1A-1 to be degraded by the UPS. However, studies have shown that SUB1A-1 is not degraded under aerobic conditions [3]. In fact, further studies have shown that SUB1A-1 has an important function in aerobic conditions. This protein can prevent the accumulation of highly toxic reactive oxygen species (ROS), which are overproduced upon sudden re-exposure to atmospheric oxygen during de-submergence [4]. These discoveries raise two questions: (1) If SUB1A-1 cannot be used to detect oxygen levels, how does rice detect submergence and initiate the corresponding responses? (2) How does SUB1A-1 escape degradation by the UPS under aerobic conditions?

Oxygen Detection under Submergence

Our research focuses on this special part of the ERF-VII family, which typically detects submergence conditions in rice and initiates the corresponding responses. In collaboration with Dr. Ming-Che Shih at the Agricultural Biotechnology Research Center of Academia Sinica, we discovered two rice ERF-VII members that can be activated by the presence of SUB1A-1 and can be degraded under aerobic conditions. Based on our findings, we propose that these two rice ERF-VII members are responsible for switching on the corresponding responses to submergence. The function of SUB1A-1 is to over-produce these two ERF-VII proteins within a short amount of time so that rice can quickly prepare for flooding. Based on our proposed mechanism, SUB1A-1 can use these two ERF-VII members to initiate the flooding responses (analogous to hibernation). During de-submergence, SUB1A-1 also helps by removing highly toxic ROS. With these two efforts, SUB1A-1 plays a crucial role for rice to resist flooding.

How does SUB1A-1 Escape Degradation?

Based on our preliminary results, the unique three-dimensional structure of SUB1A-1 prevents the oxidation of its N-degron, so it cannot be recognized and degraded by UPS under aerobic conditions. Currently, we are working on providing more supporting evidence using protein biochemistry and structural biology approaches, and we aim to reveal the molecular mechanism of how SUB1A-1 escapes degradation so that we can apply the strategy to other crops.

Conclusion

Climate change has already affected the global food supply, and the challenges will continue to grow in the face of further climate disruption and a population boom. To address these challenges, we have turned to strategies that wild rice use to survive natural disasters. Previous studies have found that the SUB1A-1 protein from wild rice cultivars can effectively help rice to resist submergence for up to two weeks. By combining bioinformatics, molecular biology, protein biochemistry, enzymology, and structural biology, we discovered that two other rice ERF-VII proteins participate in submergence detection and flood-resistance responses. We have found that a unique three-dimensional structure of SUB1A-1 prevents its degradation by UPS. Our findings extend our understanding about how wild rice cultivars withstand submergence and may help improve the hardiness of other crops in the future.

Reference

1. Xu K, Xu X, Fukao T, Canlas P, Maghirang-Rodriguez R, Heuer S, Ismail AM, Bailey-Serres J, Ronald PC, Mackill DJ. (2006) Sub1A is an ethylene-response-factor-like gene that confers

submergence tolerance to rice. Nature 442(7103), 705-708.

2. Gibbs DJ, Lee SC, Isa NM, Gramuglia S, Fukao T, Bassel GW, Correia CS, Corbineau F, Theodoulou FL, Bailey-Serres J, Holdsworth MJ.(2011) Homeostatic response to hypoxia is regulated by the N-end rule pathway in plants. Nature.479(7373), 415-418
3. Licausi F, Kosmacz M, Weits DA, Giuntoli B, Giorgi FM, Voesenek LA, Perata P, van Dongen JT.(2011) Oxygen sensing in plants is mediated by an N-end rule pathway for protein destabilization.Nature 479(7373), 419-422.

Fukao T, Yeung E, Bailey-Serres J.(2011) The submergence tolerance regulator SUB1A mediates crosstalk between submergence and drought tolerance in rice. Plant Cell 23(1), 412-427.