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Crop Readiness Level (CRL): A Scale to Track Progression of Crop Testing for Space

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The development of engineering technologies and hardware for aerospace applications is often tracked on a 1-9 scale of readiness or TRL, with a "1" representing very basic or fundamental principles, and a "9" being flight tested, functional hardware. Preparing to grow crops for supplemental food and eventual life support contributions on space missions faces similar challenges. Nearly 20 years ago, the concept of a "crop readiness level" was suggested at a bioregenerative life support conference held at Kennedy Space Center, but there was little follow up to this. We propose to revive this concept to track the preparation and testing of different crop species for eventual use in the unique environment of space. For the sake of uniformity, we recommend a 1-9 scale, with a "1" being just the identification of a potential crop, followed by some basic horticultural testing, cultivars trials, then testing growth and yield under various controlled environments, progression to more space-like environments and hardware, understanding the nutritional, organoleptic, and food safety aspects of the crop, initial testing in space, and a final stage of growing the crop for food in space ("9"). We attempted to make the scaling logical and progressive, but our main goal is to initiate a dialogue in the space, plant research community to develop a scale for assessing crop readiness.

Nomenclature

CRL	=	Crop Readiness Level
DSG	=	Deep Space Gateway
DST	=	Deep Space Transit
GCR	=	Galactic Cosmic Radiation
ISS	=	International Space Station
LED	=	Light Emitting Diode
NASA	=	National Aeronautics and Space Administration
TRL	=	Technology Readiness Level
RH	=	Relative Humidity

I. Introduction

The idea of a systematic scale for assessing and developing crops for space applications was perhaps first suggested as a tool for advanced life support systems, based on a series of workshops and meetings sponsored by NASA in the late 1990s[1] and a suggestion by Barry Finger, a bioengineer working at Kennedy Space Center. The concept was based on the aerospace engineering use of technology readiness level or TRL for tracking development and maturity of hardware or engineering components being developed for spaceflight. At that time, this concept of a crop rating system was largely focused on preparing for a NASA testbed called BIO-Plex, which was intended to be a ground analog for human life support based largely on bioregenerative systems[2, 3]. The principles were used to develop an initial crop list for BIO-Plex by a NASA "tiger team" to set priorities for plant research[4].

At that time, the proposed readiness scale was very basic and went from 0 to 3, with a readiness level of 0.0 indicating little or no knowledge of the crop in controlled environments; 1.0 indicating some controlled environment and / or horticultural testing had been conducted and results had been published; 2.0 indicating that extensive controlled environment testing had been conducted with published results, and that cultivar selection trials had been conducted; and 3.0 indicating thorough controlled environment testing, cultivar comparisons had been conducted, and that successful scale-up tests had been conducted in a closed system, such as the Biomass Production Chamber[1]. There

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were no considerations given to actual testing in a space environment, the specific nutritional attributes or horticultural requirements for the crops. These latter two factors were largely considered through various crop recommendation documents that placed emphasize on volume-efficient crops with high harvest index and high nutritional and caloric outputs[5,6,7,8,9]. But the BIO-Plex project was canceled in the early 2000's and the crop readiness level concept languished, although it has been suggested occasionally since then as a tool for future space exploration research[10]. We propose to renew and modify the idea of a "crop readiness level", with knowledge gained during the 1990s and from current International Space Station (ISS) plant growth testing in the Veggie and Advanced Plant Habitat (APH) plant growth systems to develop a standardized scale for assessing crops at the cultivar or genotype level.

Growing crops in a space environment presents numerous challenges and considerations that is driving the need for a systematic method to develop and evaluate current and future crops for in situ crop production. From a morphological perspective, current and near-term requirements favor dwarfed and other compact crops that best maximize the constrained volumes associated with space plant growth systems. Plant growth systems open to the cabin environment, such as Veggie on ISS, need to utilize crops selected to perform in a narrowly defined temperature range selected for crew comfort (21-24°C), low relative humidity levels (38-44%), and carbon dioxide levels in excess of 3000 μmol mol^{-1}[11]. Current state of the art electric lighting utilizes LEDs, with both narrow and broad spectrum capabilities available on ISS[12]. There have been observations of less-than-ideal growth, chlorosis, and necrosis in some leafy greens grown under narrow-band LED lighting[13] and in super-elevated, and occasionally moderately elevated CO_2 environments[14,15]. For most situations, UV-A and B are absent in LED lighting systems, and lack of UV has been linked to formation of potentially detrimental intumescence in a variety of crop types[16,17,18]. Studies of photoperiod effects on plant flowering, growth and development are legion[19] and control of photoperiod may be dependent on the growth chamber setting (e.g., in an open cabin environment or closed to surrounding ambient light), or perhaps all crops must be grown in one common environment, forcing a compromise set point. Temperature can affect rates of growth and leaf expansion, partitioning to different organs, pollination and fertilization, and fruit set and development in many species[20,21,22]. For example, cooler temperatures can promote tuber initiation in potatoes[23] and delay time to flowering and fruit set in tomato[24] , whereas warm temperatures can reduce time to maturity for wheat[25], and promote faster growth and increased yield in lettuce and onion[22]. But these effects and interactions with other environmental variables can be complex, and optimal ranges for temperature and other factors need to be understood for candidate space crops. As exploration destinations extend beyond low earth orbit (LEO) to deep space, future crop evaluations may need to consider the absence of a magnetic field[26] and significantly increased levels of solar particles and galactic cosmic radiation[27,28]. Perhaps growth and development at different atmospheric pressures that might be used for future space habitats should also be considered[29,30,31]. Operating in a sealed environment shared by the crew elevates the level of attention given to undesired microbial growth and activity, generation of plant litter and respiratory irritants, and release of volatile organic compounds from the crop production system[32], including volatiles such as ethylene, which can have profound effects on plant growth and development[33,34,35]. In summary, spaceflight environments can impose many constraints and selective pressures when considering types of crops (species and genotypes) that might be used. These considerations must then be combined with horticultural requirements (e.g., ease of propagation, pollination, harvesting, etc.), the nutritional values of the crops as a food source, and potential food safety challenges for growth in space[5,6,7,36].

II. Discussion

The use of technology readiness levels (TRL) is used by engineering organizations within NASA, the European Space Agency, and the US Department of Defense to assess the maturity of technologies. TRL uses a nine point scale (1-9), with "1" representing very basic or fundamental principles, and "9" being flight tested, functional hardware. We propose to implement a systematic method to track the maturity of crop development that mirrors the already established TRL scale. The goal of developing a crop readiness level (CRL) is to enable consistent testing and development of crops for use in *in situ* crop production in space. Other objectives of the CRL are to establish performance metrics for crop development activities and a method to assess and clearly communicate to a variety of audiences and stakeholders when a crop has achieved a level of development to be suitable for production in space. The intent is to identify crops and genotypes that warrant continued testing and investment for the unique environmental and operational challenges of space. CRL is meant to be focused on crop production activities and is not intended to apply to basic research that utilizes model plant organisms. The CRL scale we are suggesting for this paper is directed towards spaceflight operations in microgravity aboard ISS, with an objective of advancing to future missions such as the cis-lunar Deep Space Gateway (DSG) and Deep Space Transit (DST). As space exploration destinations and mission requirements change so will the CRL, and so one might envision CRL-specific ratings for different space destinations and mission durations

CRL Level	Title	Description
1	Basic Crop Testing	Identification of candidate crop at cultivar level. Preliminary assessment of morphology, consumable yield, germination, and mission application.
2	Cultivar Screening	Detailed assessment of plant dimensions at maximal growth, pollination and germination requirements identified, harvest index quantified.
3	Relevant Environmental Testing	Testing at ISS simulated environmental conditions. Currently this is elevated CO_2 (~3000ppm), ISS temperature (21-24C), RH (38-44%), and LED lighting absent of UV. Adverse physiological responses identified.
4	Seed Sterilization	Identification of acceptable seed surface sterilization protocol.
5	Flight-like Testing	Testing in flight or flight-analog hardware at flight environmental setpoints.
6	Chemistry & Organoleptic	Elemental and mission-specific nutritional testing conducted at flight-like conditions. Organoleptic and sensory analysis conducted.
7	Baseline Microbiology	Baseline microbiological and food safety characterization conducted under flight-like conditions.
8	Grown in Space	Crop successfully grown to maturity in space.
9	Consumed in Space	Sanctioned consumption by crew in space.

Table 1: Crop Readiness Level for Missions in Microgravity

Much like the TRL scale, CRL advances from a very basic level of understanding of a specific cultivar to the end levels, being growth and consumption in space. *Basic Crop Testing* (lvl. 1) and *Cultivar Screening* (lvl.2) are intended to be the levels when apparent incompatibilities with spaceflight operations are identified, such as incompatibilities with microgravity, plant dimensions at maturity too large for space-based plant growth systems to contain, and poor germination reliability, amongst others. *Spaceflight Environmental* (lvl.3) has been added to address some recent adverse experiences in testing of candidate ISS crops[15] and to identify other potential physiological issues such as intumescence, intolerance to various photoperiods[37], premature bolting in cold-weather adapted leafy greens[38], reduced germination, establishment, and growth in response to low humidity[39]. Current ISS flight operations require the surface sterilization of seeds prior to launch as a precautionary measure to protect crew safety[11]. *Seed Sterilization* (lvl.4) concerns the identification of a surface sterilization protocol that reduces microbial loads to acceptable levels while minimizing impacts to germination and seed storage longevity. *Flight-like Testing* (lvl.5) will be mission and system specific, with flight or flight-analog hardware being used to assess crop compatibility in an operational context. *Chemistry & Organoleptic* (lvl.6) and *Baseline Microbiology* (lvl.7) will also be done in flight or flight-analog hardware, as factors such as fertilizer types or nutrient delivery systems used in space[33,40], constrained root zone volume, and moisture levels can impact the growth, chemical, organoleptic, and microbiological properties for crops. In the current paradigm of *in situ* crop production there is an emphasis on growing crops to provide fresh food and supplemental nutrition for the crew, *Chemistry & Organoleptic* (lvl. 6) quantitates anticipated nutritional yields for space grown crops. Organoleptic and sensory analysis serves to ensure crops that are acceptable to the crew are prioritized. Current ISS flight operations require baseline microbiological and food safety characterization of edible crop tissue prior to crew consumption, this is covered in *Baseline Microbiology* (lvl. 7). Successful establishment of a crop for future space-based food production efforts is achieved in *Grown in Space* (lvl.8) and *Consumed in Space* (lvl.9).

III. Conclusion

Crops grown in space-based *in situ* crop production systems need to be subjected to additional testing and analysis to account for the unique environmental and operational challenges of space. We propose to implement the Crop

Readiness Level (CRL) scale to ensure systematic and consistent development of crops for space-based application. The current operational framework for the CRL is directed at operations aboard the ISS, with future microgravity exploration destinations such as Deep Space Gateway and Martian transit missions also included. As operations and mission requirements change (e.g. surface operations; caloric replacement) the CRL scale will also need to change. We hope this effort starts a dialogue with the scientific and human exploration community to further develop and refine the proposed CRL scale.

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