

A Uniform, Objective, and Adaptive System for Expressing Rice Development

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ABSTRACT

The large area of rice (*Oryza sativa* L.) production worldwide is critical to the well being of large numbers of the world's people. Yet for rice, the most important single plant species for human nutrition, there is not a widely used growth staging system. Despite good points of the published rice growth staging systems, none has been used widely for describing rice growth and development. Consequently, an objective growth staging system with enumeration adapted to cumulative leaf number (CLN) would improve communication among scientists, farmers, and educators. We propose a rice developmental staging system divided into three main phases of development: seedling, vegetative, and reproductive. Seedling development consists of four growth stages: unimbibed seed (S0), radicle and coleoptile emergence from the seed (S1, S2), and prophyll emergence from the coleoptile (S3). Vegetative development consists of stages V1, V2 . . . VN; N being equal to the final number of leaves with collars on the main stem. Reproductive development consists of 10 growth stages based on discrete morphological criteria: panicle initiation (R0), panicle differentiation (R1), flag leaf collar formation (R2), panicle exertion (R3), anthesis (R4), grain length and width expansion (R5), grain depth expansion (R6), grain dry down (R7), single grain maturity (R8), and complete panicle maturity (R9). Assigning rice growth stages based on discrete morphological criteria will result in unambiguous growth-stage determination. For example, using this system, two people staging the same plant will arrive at the same growth stage. This is because the system exploits the presence or absence of distinct morphological criteria in a symbolic logic dichotomous framework that only permits yes or no answers.

RICE GRAIN is a food staple for more people than foods obtained from any other single plant species. Major portions of the world obtain more than half of their daily dietary calories from rice. Consequently, rice research and its application potentially affects the well being of a large part of the world's human population.

Biological understanding and practical value of crop growth staging systems have been progressive and cumulative. Crop growth staging systems are meant to be an aid in information transfer for crop management. They can also aid scientists and others in observing, recording, and communicating critical crop growth data. Yet for rice, the most important single plant species for human nutrition, there is not a widely used growth staging system. We found four published systems for describing rice development: Zadoks et al. (1974), IRRI

(1980), the BBCH system (Lancashire et al., 1991), and Haun (1973). Zadoks et al. (1974) is an adaptation of Feekes' (1941) scale (with 23 subdivisions) but further delineated. The IRRI (1980) scale is a 10-point system (0–9) with no subdivisions. The BBCH (Lancashire et al., 1991) system for rice is an adaptation of the Zadoks et al. (1974) scale. Consequently, the BBCH and Zadoks et al. scales are 99 and 110 point systems, respectively. Haun (1973) also described a wheat (*Triticum aestivum* L.) developmental system that has been applied to rice. Haun's system is enumerated into CLN. All four systems have strengths and all share problems related to enumeration of growth stages and criteria for the determination of the growth stage. Despite good points of the published rice growth staging systems, none has been used widely for describing rice growth and development.

Terms that have been used to describe plant developmental time include plastochron and phyllochron. Plant age can be expressed in a biologically meaningful way by the CLN produced on the main stem. The time interval between successive leaf initiations is called a *plastochron* (Langer, 1972). The problem with determining the *plastochron* is that the initiated leaves are not visible without microscopy. A *phyllochron* is the time interval between the same leaf developmental events of successive leaves (Rickman and Klepper, 1995; Wilhelm and McMaster, 1995; Nemoto et al., 1995).

The concept of plant age by CLN was implicitly recognized by Bonnet, Kepler, Leonardo da Vinci, and perhaps Aristotle (Jean, 1994). The incorporation of plant age (as determined by CLN) into developmental systems has been progressive. Feekes (1941) essentially ignored the delineation of vegetative growth into phytomers in his system for wheat. Higgins et al. (1964) reported on CLN as a means of expressing plant age. Hanway (1963, 1966) recognized that corn (*Zea mays* L.) develops by CLN but did not enumerate his stages by CLN. Rather, he stayed with the enumeration proposed by Feekes (1941). However, Hanway did recognize CLN to a degree in his corn system. Haun (1973) appears to have been the first to incorporate CLN into the enumeration of a crop growth staging system. Haun recognized the modular nature of vegetative development for wheat and allowed his enumeration to be set by the plant, that is by the CLN (x in Haun's system), rather than an arbitrary number (e.g., 10, 11, 99, or 110). The discrete aspect of Haun's wheat development system was combined with the continuous criteria of the partial development of elongating leaves. Fehr and Caviness explicitly recognized CLN and incorporated three important advances into their soybean [*Glycine max* (L.) Merr.] growth staging system:

Abbreviations: CLN, cumulative leaf number; IE, internode elongation.

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1. They implicitly recognized that CLN, phyllochron, and plastochron are biological phenomenon not limited to grasses.
2. Since vegetative and reproductive development proceed simultaneously, the staging system should reflect this simultaneous development.
3. They provided dichotomous criteria for the beginning of their growth stages.

Fehr and Caviness, like Haun, allowed the enumeration of the vegetative growth stages to be determined by the plant rather than being imposed arbitrarily upon it. Vegetative development was delineated and determined simply by leaf number without attempting to determine subsequent leaf elongation. Consequently, two people independently examining one soybean plant using the Fehr and Caviness system will arrive at the same growth stage.

If incorporated into existing systems, a crop growth staging system based on plant morphogenesis, with each stage differentiated from another dichotomously, would facilitate consistent crop growth staging. For example, two people would arrive at one answer for the growth stage of one plant. The dichotomy referred to is the symbolic logic framework for phrasing questions. Primarily discrete criteria are employed because criteria determined by quantitative measurement (e.g., length and width) are plastic and consequently productive of equivocal growth stage determinations. An objective morphological criterion is either present or absent; thus, for the question of whether a plant is at a given growth stage, the answer is either yes or no.

There are several systems in place to express various stages of rice development. Some are adapted to a small area of land across which conditions are consistent enough to make applicable assumptions about plant growth and development. These assumptions do not hold true for a larger area of land. In the Arkansas, Louisiana, Mississippi, and Texas rice growing areas, the differentiation of the panicle into branches is coincident with the first internode to elongate much more than its own width. Therefore, in Arkansas the stage of growth is called *internode elongation* (IE). By splitting the culm in half lengthwise, the differentiating panicle is visible as well as the first elongated internode. This is the stage of development when the N demand by the developing panicle is relatively high and which the rice crop has been responsive to midseason N fertilization. The *green ring* is the dark green circle found by slicing across the vertical axis of the rice culm just below the closely stacked initiated final leaves of the culm and the initiating panicle. Now, logically, supplying N at green ring would provide adequate N for the soon-to-be differentiating panicle. Both green ring and IE are easily visible without magnification. Farmers, salesmen, extension personnel, and researchers in Louisiana and Arkansas are familiar with the terms green ring and IE, so these terms are valuable. The problem with both terms is that they are indirect guides to the actual events of interest — panicle initiation and differentiation. In some cases

panicle differentiation can occur without IE. Clearly what is needed is a system for expressing the actual event rather than the indicator. The use of the terms green ring and IE to manage the rice crop is adequate within proscribed areas but inaccurate or irrelevant in others. Consequently, in some locations the terms panicle initiation and differentiation are employed for the sake of scientific precision. Moreover, while panicle initiation is an event at a point in time, panicle differentiation is a process through time. The term *panicle differentiation* refers to differentiation of the panicle branches.

The power of the local jargon and systems is that they are concise and only growth stages needed for management decisions are identified. Consequently, local systems are simple, short and rely on visible markers. However, when new management decisions are required, the short local systems must often be expanded to address the new problems. Also, application of research results useful to farmers, educators, and researchers across large geographical areas is often impossible because of imprecise growth stage expression that may mean one thing in one area and another elsewhere. Consequently, a precise, objective, and adaptive rice growth staging system is needed for present application and future needs of farmers, educators, and researchers.

The primary value of an objective and adaptive crop growth staging system is enhanced communication among farmers, consultants, crop insurers, scientists, teachers, and extension personnel. The central feature that allows meaningful communication is the ability to objectively determine the growth stage. The dichotomous feature assures that different people staging the same rice plant will obtain the same crop growth stage. The visibility of criteria is also critical to the system. It is more convenient in the field to observe things visible to the naked eye or with a small hand lens ($\approx 10\times$ magnification) rather than requiring a microscope. Consequently, plant morphological features visible with magnification less than or equal to $10\times$ were favored as growth stage criteria. An adaptive rice growth staging system based on objective, visible, and discrete morphological developmental criteria can improve the usefulness of temperature time units with precise CLN time units.

Morphogenesis

Rice morphological development can be divided into three phases: seedling, vegetative, and reproductive. These three phases are described in detail below. The late vegetative phase and the early reproductive phases occur simultaneously. The seedling and reproductive stages progress through a series of unique (occurring only once during development) events, whereas the vegetative stages progress through an iterative sequence of leaf developmental events. Thus, the phytomers are true examples of gnomonic development (incremental development in which each increment added to a structure results in a new structure resembling the original) (Jean, 1994).

Table 1. Characteristics of rice used in field experiments conducted at the Rice Research and Extension Center at Stuttgart, AR and at the Northeast Research and Extension Center near Keiser, AR in 1998.

Cultivar	Characteristics
Carolina Gold	300-yr-old U.S. rice cultivar
Drew	Arkansas long-grain rice released in 1997
Guichao2	South China rice cultivar with round grains and nonsticky texture
Lemont	Texas long-grain rice released in 1982
M11-131	Line developed from cross of Lemont and Bond
M202	California medium-grain rice cultivar
Qiguizao	South China, long-grain rice cultivar

Seedling Development

To germinate, a dry rice seed must imbibe water. In germinating seeds, either a coleoptile or a radicle may emerge first. In dry-seeded conditions the radicle may emerge first, but in water-seeded conditions the coleoptile may emerge first. However, in at least some rice cultivars the coleoptile emerges before the radicle in dry-seeded conditions. A prophyll (rudimentary leaf) emerges from the coleoptile. This is followed by the emergence of the first leaf (one with a blade and sheath) above the prophyll. In low O₂ conditions, such as in water-seeded rice, the emergence of the radicle may occur after the emergence of the first complete leaf.

Vegetative Development

Vegetative growth occurs in distinct, biological units of development time. The period between leaf collar formations on successive leaves is one measure of a phyllochron that is easily determined without magnification. We chose to employ successive collar formations for the vegetative growth stage determinations.

Vegetative development also occurs in distinct structural units called phytomers. A *phytomer* is the unit of vegetative development consisting of a leaf (blade and sheath) and its subtended node, internode, nodal roots, and tiller bud (Hoshikawa, 1989). Each complete (i.e., containing both sheath and blade) leaf on the main stem beginning with the first leaf can be marked as having completed elongation with collar formation. Note that collar formation is also one part of the completion of one phytomer or vegetative building block.

Reproductive Development

Reproductive development begins when the shoot apex begins initiation of panicle structures. Subsequently, the panicle branches differentiate; the florets differentiate, including male and female organs as the panicle enlarges concurrently with the rest of the rice culm; microsporogenesis and megasporogenesis occur; the panicle emerges; anthesis occurs; the caryopsis elongates; the grain fills with starch; the grain ceases to fill; and the grain dries down. The nature of the grain continues to develop after harvest, leading to changes in the chemical and physical characteristics of the endosperm. Very detailed wheat apex development is provided by McMaster (1997) and detailed development of the rice plant is provided by Hoshikawa (1989) and by

a later volume translated from Japanese (Matsuo and Hoshikawa, 1993).

Purpose

The purpose of this paper is to present a uniform, adaptive system for expressing rice development.

MATERIALS AND METHODS

The primary methods leading to the development of the system were (i) observing rice plants as they developed, (ii) noting dates of phenological events on the same plants, (iii) studying the literature on plant development and growth staging, and (iv) reflectively discussing these. Discussions were held with scientists from several disciplines to elucidate rice growth stages that were important to their discipline. Literature searches were made and an objective, adaptive rice growth staging system was presented and discussed on 4 Mar. 1998 at the Rice Technical Working Group in Reno, NV (Counce, 1998). Also, a workshop was held on 3 Sept. 1998 in Stuttgart, AR to demonstrate the system and to query participants about the system. There were several points raised in the discussion session that required further clarification either by literature searches or through experimental observation. The following experiments and observations were used to provide clarification where needed.

Seedling Growth Stages

Laboratory, growth chamber, and greenhouse experiments with water imbibition and seedling germination were used together with several years of field observations to delineate seedling stages. The procedure was to take 100 rice seeds of different cultivars and seed lots and place them in aerated tap water at a constant temperature of 25°C. Each day, seedlings with visible radicles and coleoptiles were counted.

Vegetative Growth Stages

Seeds of 'Carolina Gold', 'Drew', 'Guichao2', 'Lemont', 'M11-131', 'M202', and 'Qiguizao' rice were planted on 12 and 13 May 1998 at the Rice Research and Extension Center near Stuttgart, AR on a Crowley silt loam soil (fine, smectitic, hyperthermic Typic Albaqualf). These cultivars and some characteristics are listed in Table 1. Beginning on 21 May 1998, plants were tagged when the prophyll leaves began to emerge from the coleoptiles. The date of collar formation for the first leaf was noted. Subsequently, collar formation for each successive leaf on the main stem was noted. A group of the same varieties grown at the Stuttgart location were also grown at the Northeast Research and Extension Center near Keiser, AR on a Sharkey silty clay loam (very-fine, smectitic, thermic Chromic Epiaquert). At Keiser, rice was planted on 26 May 1998. On 23 July 1998, Drew, Lemont, and M202 were planted at the site near Stuttgart and notes were taken as for the earlier planting. On 8 Aug. 1998, Drew was planted at the site near Stuttgart and notes were taken as for the earlier plantings. Observations on selected plants were made Monday through Saturday until anthesis occurred. One day per week, plants were not observed and leaf emergence noted on the subsequent day was marked to denote that the actual date of collar formation could have been either of 2 d.

In August 1998 a farmer's rice field near El Campo, TX was visited to make observations on plants from a ratoon rice crop. In the growth chambers and greenhouses at Stuttgart and Keiser, AR, experimental observations on main stem and

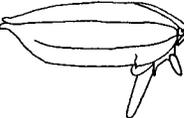
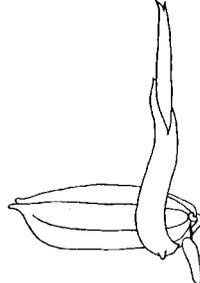
Growth Stage	S0	S1	S2	S3
Morphological Criteria	Dry, unimbibed seed	Emergence of coleoptile	Emergence of radicle	Emergence of prophyll from coleoptile
Illustration				

Fig. 1. Rice seedling growth stages with morphological markers. The sequence of normally occurring seedling developmental events is presented. There are exceptions to the sequence given. In some cases the rice coleoptile emerges from the seed first and in other cases the radicle emerges first. When either emerges alone the growth stage is S1. When both have emerged, the growth stage is S2. If the prophyll emerges from the coleoptile before the radicle emerges from the seed, the growth stage is S3; the prophyll is the first leaf to emerge, but it lacks a blade and collar and consists only of the leaf sheath.

tiller leaf number development with time have been made since 1989.

Reproductive Growth Stages

Examination of rice panicle and grain development has been carried out since 1989. In 1997, individual panicles and grains were examined during the course of their development to propose the staging system. Confirming observations were made in 1998 in the field.

RESULTS AND DISCUSSION

Description of the Rice Crop Growth Staging System

We propose a rice developmental staging system divided into three main phases of development: seedling, vegetative, and reproductive.

The sequence of normally occurring seedling developmental events consists of four growth stages: unimbibed seed (S0), radicle and coleoptile emergence from the seed (S1, S2), and prophyll emergence from the coleoptile (S3). There are exceptions to the sequence of events presented. In some cases the rice coleoptile emerges from the seed first and in other cases the radicle emerges first. When either emerges alone then the growth stage is S1. When both have emerged, the growth stage is S2. If the prophyll emerges from the coleoptile before the radicle emerges from the seed, then the growth stage is S3. The prophyll is the first leaf to emerge, but it lacks a blade and a collar and consists only of the leaf sheaf. The seedling growth stages, illustrations, and morphological criteria for each growth stage are presented in Fig. 1.

Vegetative development consists of stages V1, V2 . . . VN; with N being equal to the final number of leaves with collars on the main stem. Vegetative structures

relative to the system are illustrated in Fig. 2. The vegetative growth stages allow us to exploit the iterative nature of vegetative development. Each leaf is succeeded by an additional leaf until the formation of the

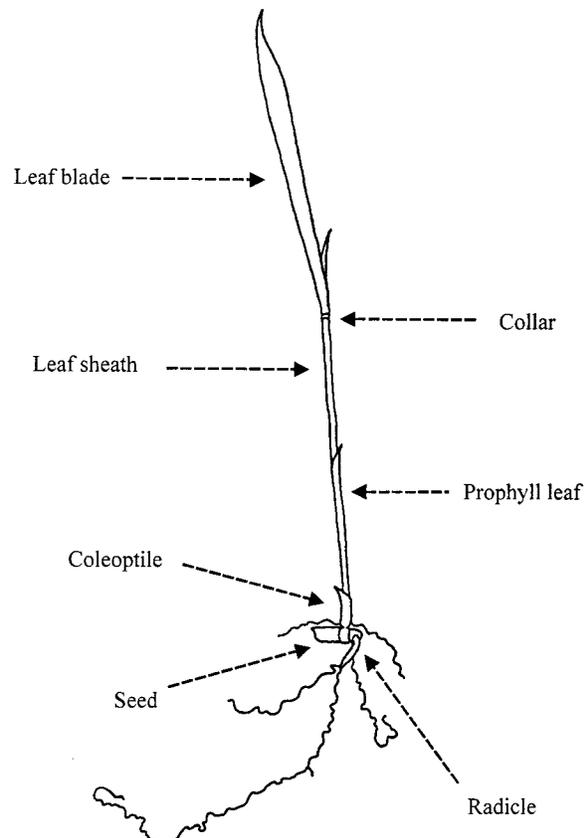


Fig. 2. External morphological structures of a V1 rice plant relative to the growth staging system.

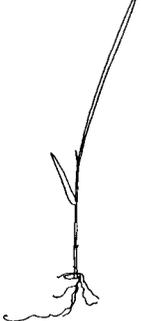
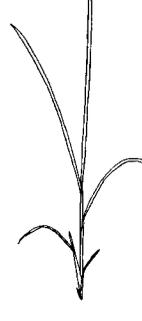
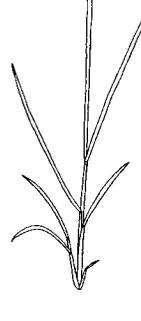
Growth Stage	V1	V2	V3	V4	V5
Morphological Marker	Collar formation on first complete leaf (Leaf 1) on main stem	Collar formation on Leaf 2 on main stem	Collar formation on Leaf 3 on main stem	Collar formation on Leaf 4 on main stem	Collar formation on Leaf 5 on main stem
Illustration					
Growth Stage	V6	V7	V8	V9 (V _{F-4})	
Morphological Marker	Collar formation on Leaf 6 on main stem	Collar formation on Leaf 7 on main stem	Collar formation on Leaf 8 on main stem	Collar formation on Leaf 9 on main stem	
Illustration					
Growth Stage	V10 (V _{F-3})	V11 (V _{F-2})	V12 (V _{F-1})	V13 (V _F)	
Morphological Marker	Collar formation on Leaf 10 on main stem	Collar formation on Leaf 11 on main stem	Collar formation on Leaf 12 on main stem	Collar formation on Leaf 13 (flag leaf) on main stem	
Illustration					

Fig. 3. Rice vegetative growth stages with morphological markers for a rice cultivar with 13 true leaves on the main stem. The number of vegetative growth stages varies with the number of true leaves on the main stem. V_F denotes flag leaf and it follows that V_{F-n} denotes the *n*th node before the flag leaf (V9-V13).

Growth Stage	R0	R1	R2	R3	R4
Morphological Marker	Panicle development has initiated	Panicle branches have formed	Flag leaf collar formation	Panicle exertion from boot, tip of panicle is above collar of flag leaf	One or more florets on the main stem panicle has reached anthesis
Illustration					
Growth Stage	R5	R6	R7	R8	R9
Morphological Marker	At least one caryopsis on the main stem panicle is elongating to the end of the hull	At least one caryopsis on the main stem panicle has elongated to the end of the hull	At least one grain on the main stem panicle has a yellow hull†	At least one grain on the main stem panicle has a brown hull‡	All grains which reached R6 have brown hulls
Illustration					

Fig. 4. Rice reproductive growth stages with morphological markers. Other authors have chosen to use the terms “physiological maturity” or “cessation of dry matter accumulation” (R7). We avoid these terms because for rice such determinations are difficult or impossible to make with any known morphological marker. The brown hull indicates the grain has begun to dry (R8 and R9).

final leaf on a culm, the flag leaf. A phyllochron usually varies from 3 to 8 d (80–115 degree day units calculated as the mean of high and low daily temperatures –10 in °C). Late vegetative developmental stages (V_{F-4} – V_F) and early reproductive developmental stage (R0–R2) occur simultaneously. The vegetative growth stages, illustrations, and morphological criteria for each growth stage are presented in Fig. 3.

Reproductive development consists of 10 growth stages based on discrete morphological criteria: panicle initiation (R0), panicle differentiation (R1), flag leaf collar formation (R2), panicle exertion (R3), anthesis (R4), grain length, and width expansion (R5), grain

depth expansion (R6), grain dry down (R7), single grain maturity (R8), and complete panicle maturity (R9). Stages R0 through R3 refer to the developing panicle, while Growth Stages R4 through R8 refer to the individual florets or grains on a panicle. If any florets or grains on a main stem panicle have passed into the next R stage for Stages R4 to R8, then the plant is determined to be at that R stage. Thus, if one grain on a panicle has a caryopsis filling the cavity of the lemma and palea (the hull), then the growth stage is R6. The grain hulls (the lemma and palea) for rice are green from R4 through R6. Growth stage criteria grains are yellow in R7 and brown in R8 and R9. Usually, the first grains

RICE DEVELOPMENTAL TIME LINE

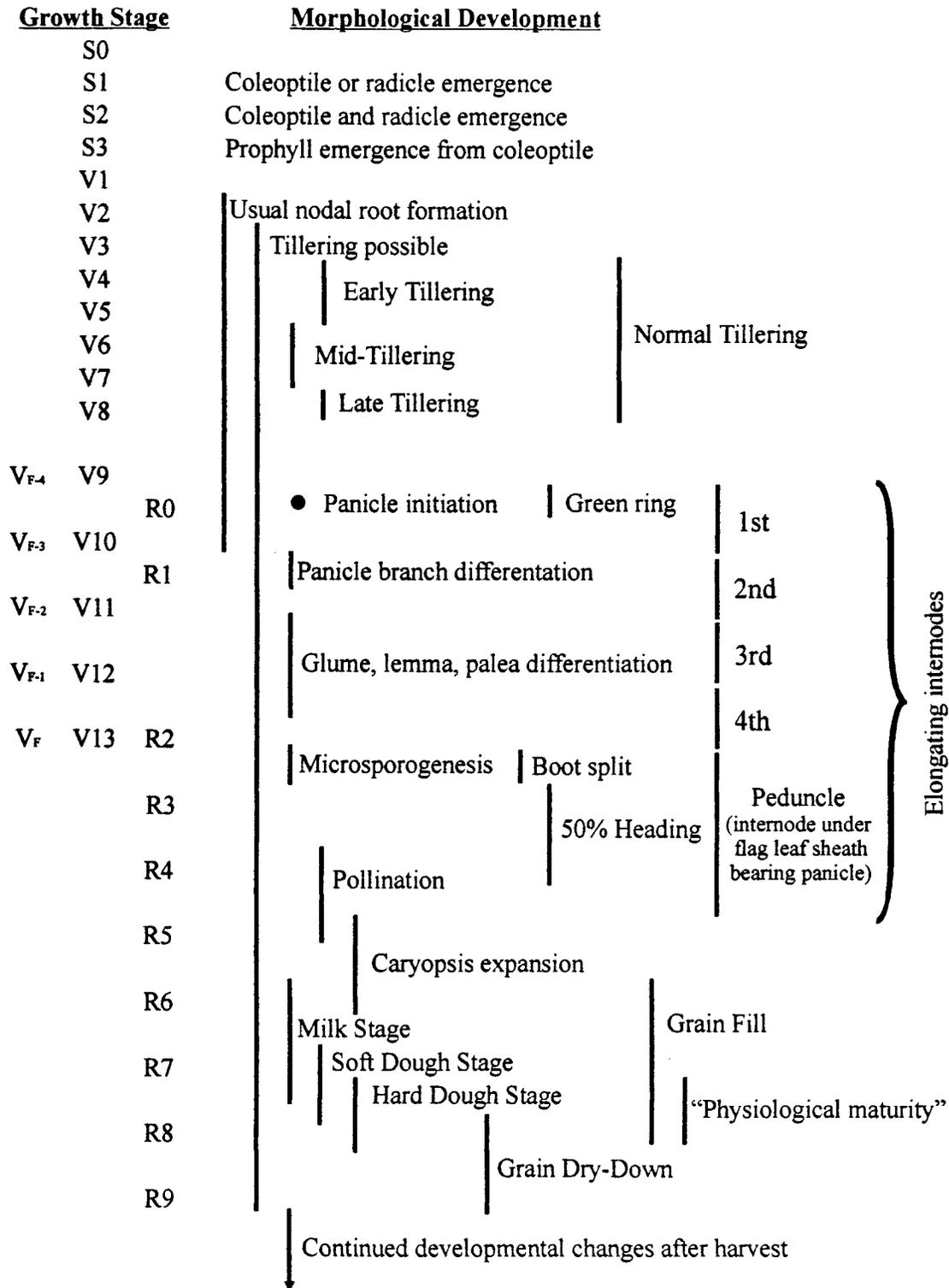


Fig. 5. Time line for rice growth stages and morphological changes in the rice plant.

to be at the criteria stages of development will be the grains at the top of the panicle because the upper grains initiate growth prior to lower grains. Growth Stage R9

refers to all grains on main stem panicles that had reached Growth Stage R6. Often harvest will be done before all plants have reached R9. The reproductive

growth stages, illustrations, and morphological criteria for each growth stage are presented in Fig. 4.

Rice Developmental Time Line

Normal morphological developmental events are juxtaposed with the growth stages in Fig. 5. Since some growth stages are defined by certain morphological criteria, they occur simultaneously (e.g., R0 and panicle differentiation, R4 and the beginning of pollination). Other events occur near the time or may not occur at all, such as “elongation” of the first “elongating” internode. The term “physiological maturity” is included to show when that undefined term with no criteria may occur. Seeds are certainly viable by R9 but may be viable much earlier. The grains (seeds) continue to change physically and chemically after harvest, consequently development continues after harvest, as noted on Fig. 5.

Expansion of the System to Include Quantitative Criteria

The system can be expanded to include quantitative criteria if so desired. Continuous criteria for growth stage determination could include growth stages for prophyll elongation completion, which could be known as V0 but has no discrete criterion.

Microsporogenesis in some situations is an important event for crop management. The criteria for determining microsporogenesis is continuous and not discrete. It normally occurs during the R2 growth stage. This could be a growth stage denoted by R2_{ms}. The criterion for Growth Stage R2_{ms} would be continuous, not discrete: elongation of the sheath of the flag leaf to the midpoint in the height of the leaf sheath of the preceding leaf (which is at vegetative Growth Stage VF) and Reproductive Growth Stage R2. Microsporogenesis is not always but often associated with the criterion proposed for R2_{ms}. To be certain of microsporogenesis, microscopic examination of the florets is required.

Expansion of the system to include quantitative or microscopic criteria may be useful for some applications. The meaningfulness of such expansions will be of limited value outside a small area in most cases.

Enumeration of a Crop

The growth stages refer to individual plants, main stems, or grains. It is useful to have a way to quantitatively express the stage of development for a field. Fehr and Caviness (1979) and others suggested enumeration of individuals in a population, and if more than 50% had advanced into the next growth stage, then the crop was reckoned to be in the next growth stage. Individual grain maturation in the panicle can occur in more than one grain simultaneously. To enumerate a field within seedling, vegetative, or reproductive growth stages, take the average of the growth stages for the plants staged. Note that field enumeration cannot be averaged across growth stage divisions (i.e., seedling, vegetative, or reproductive). The decimal part of the average indicates the tendency of the plants on average to advance to the next growth stage. For instance, if three plants were

staged from one field and one plant was at V5, one at V7, and one at V8, the growth stage would be V6.7.

CONCLUSIONS

A uniform system for expressing rice development was presented. The system employs dichotomously applied objective morphological criteria for growth stage determinations. Enumeration is adapted to the CLN of the plant's main stems. The system can be used to determine stage of growth in an objective, unequivocal manner so that communication of rice research results and producer practices can be facilitated.

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