A stochastic cellular automata model for rice tillering in the system of rice intensification

Monamorn Precharattana\textsuperscript{1, 3} and Tanaporn Kajonphol\textsuperscript{2}

\textsuperscript{1}Institute for Innovative Learning, Mahidol University 73170, Thailand
\textsuperscript{2}Faculty of Natural Resources and Agro-Industry, Kasetsart University, Chalermprakiat Sakon Nakhon Province Campus, 47000, Thailand
\textsuperscript{3}Email: mprecharattana@hotmail.co.th

Abstract. Closing the yield gap of rice production is urgently needed to improve food security in the ever-expanding world population. We propose a stochastic cellular automata (CA) model to describe spatial dynamics of rice growth under the system of rice intensification (SRI) to identify best planting practise. Our simulation results reveal sigmoid growth pattern of typical rice vegetative growth. We found that the exponential growth phase was dominantly influenced by the initial planting density, while the saturation growth phase was dominated by the initial spacing density. Planting of one or two or three plants per hill appeared to be suitable for the initial spacing density of 30 x 30 cm$^2$, 40 x 40 cm$^2$, 50 x 50 cm$^2$ or larger, respectively. Our CA model can be used to describe the dynamics of rice vegetative growth, which may be a predictive feature of rice yield.

1. Introduction
Climate change and global warming contributes to the emergence of many risks in agriculture [1, 2]. At farm level, the risk factors mostly include lack of water resources and poor production management. To double rice yield and solve this problem, a new technique called the System of Rice Intensification (SRI) [3] was established by Thai National Economic and Social Development Plan as a key guide to improve agricultural development [4, 5], expecting to reduce the cost of water resources by more than half when compared to a conventional farming [6]. Amongst different terrains, it is difficult to predict how successful is the new technique, and how cost-effective is the resource management model. However, there is a very limited number of studies in SRI cultivation at farm level, due to its time-consuming process and a large area of land required. Therefore, a study on rice growth management using SRI technique in various rice cultivated areas is needed.

Several ordinary differential equation (ODE) models, for instance ORYZA1 [7], RICEMOD [8], CERES-RICE [9], SIMRIW [10], have been applied to evaluate the efficacy of agricultural production process and management strategy to reduce risk and to analyze long-term cropping systems. Although the ODE model seems to be useful to describe various aspects of plant growth dynamics and management, a spatial growth of rice plants might not well-suite with the models. Additionally, these continuous based models might be insufficient to describe local interactions and to construct an accurate simulation demonstrating the spatial distribution of the rice in tillering of different initial spacing density and the initial planning density.

To improve accuracy and to reduce time and natural resource consumption of field experimentations, we develop a discrete mathematical model. The consideration of rice growth as a
form of spatial discontinuity would explain the dynamics of individual rice growth and, in the future, might be able to predict the yield of rice crop in paddy fields of various areas and planting conditions. To study the spatial growth of individual rice plants grown in a paddy field of various planting conditions, we thus propose a discrete dynamic system, called a cellular automaton (CA) model in which we assume that the system of interest consists of a collection of regular spatial grids. Each grid exists in one of a defined number of specified states. The dynamics of the system are processed by changing the specified state of the grids per a set of local rules depending on the state of the grids and those of its neighboring grids [11]. Of the function \( p \in [0, 1] \), the rule for a 2D CA, \( S_{ij}^{t+1} = F[S_{ij}^{t}] \), is solely applied at a grid of a random variable \( v \leq p \left(S_{ij}^{t}\right) \). At each step, a random number \( v \) is generated for each grid \((i, j)\), and the new state is updated only when the generated random number is less than \( p \), otherwise it remains unchanged. The advantage of CA is that it could model complex dynamical phenomena by reformulating macroscopic behaviors into microscopic or mesoscopic levels. A set of rules specifies the time and space evolution of the system, which are discrete in both variables. The use of CA has attracted a great deal of interest in recent years where CA can show very complex evolution patterns [12]. It is also well-known that repeating applications of simple rules lead to extremely complex behavior that can emulate physical, social and biological systems [13]. CA can also explain and predict changes in dynamics of environment systems and agricultural systems, for instance, the simulations of an individual plant growth [14, 15], population dynamics [16], and community interaction levels [17].

We are interested in applying CA model to describe the rice growth dynamics because rice is characterized by spatial growth involving lateral expansion to the surrounding area, and we focus on rice vegetative growth phase because number of tillers is likely to reflect yields [18]. Because SRI is a technique of rice cultivation based on the principle of water management associated with land management, we focus on patterns of rice tillering in various planting conditions by considering (i) the initial spacing density and (ii) the initial planting density. We expect that the CA approach would provide an alternative software tool for estimating rice growth dynamics in various planting conditions. We describe field experimentation, data collection and data transformation into parameters for computational system. We demonstrate how our proposed model help to explain the dynamics growth rate of an individual rice. We also compare simulation results obtained from the field experiments to identify a suitable model. Lastly, we discuss key factors that influence rice growth and recommend the best rice planting condition.

### 2. Field experiments and rice cultivation system

Field experiments were conducted at Faculty of Natural Resource and Agro-Industry, Kasetsart University (Sakon Nakhon Campus), located in the Northeast of Thailand. Rice crop was grown on sandy soil during dry season (March to May of 2016) of a tropical humid, without rainfall, and monthly mean air temperature ranged from 21 to 35°C.

A 3x4 factor factorial experiments comprised of three initial planting density conditions [viz. transplanting with one plant per hill, two plants per hill, and three plants per hill] and four initial spacing density conditions [viz. 25 x 25 cm², 30 x 30 cm², 40 x 40 cm², and 50 x 50 cm²] were established in a randomized, completed design sized 24 m² with three replications.

The non-photosensitive 120-days old rice hybrid *Chai Nat 1* was grown under system of rice intensification (SRI) for water management technique [3]. Rice seeds were sown in nursery plots at the beginning of February and 25-days-old seedlings were then transplanted to the SRI managed-plots. In the SRI system, indicator scales were placed in each plot to observe water level. Plots were maintained with a water level of 5 cm during irrigation period and were alternated with a water level of 20 cm below the soil surface during non-irrigation period. Irrigation after a non-irrigation period was continued for the specified vegetative growth period as per treatment up to the flowering stage. Subsequently, water level was maintained above soil level until grains reached hard dough stage, i.e. two weeks before harvesting, and then drained out to facilitate grain drying. Chemical fertilizers and treatments were applied in the growth management systems.
To investigate dynamics of the rice growth during tillering phase, the number of rice tillers of an individual rice clump were counted every 3 days in each planting condition with 6 samples in every sub-plot. The number of rice tiller of an individual clump were calculated and presented in averaged mean tiller including standard error of the mean for dynamics of the rice tillering. The initial spacing density for 25 x 25 cm² transplantation with one plant per hill, two plants per hill, and three plants per hill, with planting condition designated as T1, T2, and T3, respectively. Following the same method, the initial spacing density for 30 x 30 cm² transplantation with one plant per hill, two plants per hill, and three plants per hill were named as T4, T5, and T6, respectively. Those for 40 x 40 cm² and 50 x 50 cm² are named T7, T8, T9, and T10, T11, T12, respectively.

3. Stochastic cellular automaton model for dynamics of rice tillering

We employed a computational system to characterize our model, including cell state, initial condition and data collection, updated rules, and used parameters to be proposed and presented to describe dynamics of an individual rice growth.

3.1. Lattice and state of the cell

A 2D cellular automaton is developed to investigate a vegetative growth phase of an individual rice in a paddy rice field. One cell grid is defined as 1 square centimetre which represents either the soil position, or the position of an offshoot of rice varying in each rice growth state. The states of a rice offshoot and the meaning of their states are:

- SEEDLING: a young rice shoot cultivated under a suitable condition in a seedling paddy until it is ready and strong enough to thrive in the rice field. It is the initial state of rice which is planted into the field.
- CLUMP: a state of rice that developed from the SEEDLING state. It is the first state of rice suitable for tillering.
- PRIMARY TILLERING: an offshoot that sprouts up from a CLUMP.
- SECONDARY TILLERING: an offshoot that sprouts up from a PRIMARY TILLERING.
- TERTIARY TILLERING: an offshoot that sprouts up from a SECONDARY TILLERING. This is the final state of rice in vegetative growth phase.

3.2. Initial condition, data collection, CA Rules and used parameters

3.2.1. Initial condition and data collection. The initial configuration is depicted as a rice paddy field planted with Day 25 SEEDLING state of rice (equal to Day 1 in SEEDLING state in computational field) with the combination between different planting density conditions [viz. transplantation with one plant per hill, two plants per hill, and three plants per hill] and spacing density conditions [viz. 25 x 25 cm², 30 x 30 cm², 40 x 40 cm², and 50 x 50 cm²]. Fixed boundary condition is used. To process each configuration, the state of each rice offshoot, affected by the eight adjacent cell neighbours based on the Moore neighbourhood definition [19], is updated according to the CA rules. Then, number of each type of rice offshoot is counted and noted. The configuration is announced as one-time step, being taken as one day in real life.

Although soil quality, water, and solar radiation are the main factors affecting plant’s growth, our model considers only in rice farming under suspicion of land management by focusing on the differences in planting density and in spacing density at the same cropping area and location. Therefore, the quantity and the quality of the factors are viewed as energy sources obtained by rice plants and are translated into “rice growth rate” along with the effects of planting density and spacing density for each planting condition of ours.

3.2.2. CA Rules. Rule 1: Update rule for SEEDLING

A SEEDLING becomes a CLUM if \( \tau_{rice} = \tau_{day.mother.start} \). Otherwise, the SEEDLING stays unchanged its state (at \( \tau_{rice} < \tau_{day.mother.start} \)).
Table 1. Used parameters, and its meaning and value.

| Used parameters          | Meaning and Values                                                                                                                                                                                                 |
|--------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\tau_{\text{rice}}$    | The age of the initial SEEDLING and its offshoots in the unit of Day. The age of the offshoot that sprouts from its mother trunk will be the same age as its mother due to clonal reproduction.                                      |
| $\tau_{\text{day, mother, start}}$ | The age of rice in SEEDLINGS state that becomes the CLUMP - the state of rice that is ready to start sprouting in the next day. This variable depends on the rice varieties. In Chai Nat 1, we supposed it to be Day 11 (35 rice days old), according to the results from our rice field experiments. |
| $\tau_{\text{age, start, regress}}$ | The age of rice beginning to reduce the rate of sprouting. For Chai Nat 1, the value is supposed to be Day 36 (60 rice days old) in our simulation.                                                                         |
| $P_{\text{sprout}}$     | Probability in sprouting of the rice a given date is calculated by $P_{\text{sprout}} = P_{\text{internal factors}} \times P_{\text{external factors}}$                                                                 |
| $P_{\text{internal factors}}$ | The probability of rice’s sprouting due to internal factors such as aging, or genetic predisposition during tillering.                                                                                                 |
| $P_{\text{external factors}}$ | The probability of rice sprouting due to external factors: the density of rice in a specified area where the rice can absorb nutrients from soil and water, or get energy from sunlight to nourish itself, where $P_{\text{external factors}} = 1 - \frac{N_{\text{shoots at t = } \tau_{\text{rice}}}}{C_{\text{sprouting}}}$ |
| $P_{\text{ini, internal factors}}$ | The probability of rice to begin sprouting; this parameter is important for determining how much rice can be grown. We suppose this value is tentatively varied according to the space size for initial planting, but inversely varied according to the initial planting density. Because a larger space trends to have more nutrient more than the smaller one, so that a mother trunk is strong and sprout well. When a lot of seedling per hill was carried out in the initial planting, a seedling competes for limited nutrients with other seedlings. The initial probabilities of internal factors of rice growth for each planting condition in our model estimated from our field experimental results are as follows: |
| $N_{\text{shoots}}$      | The number of rice’s shoots per hill.                                                                                                                                                                              |
| $C_{\text{sprouting}}$  | A maximum capacity of rice tillering related to the planting space. The parameter represents the effects of plant spacing density, which is one of external factors affecting the capacity of rice in tillering. It shows the amount of food per unit area in cultivation. |

**Rule 2:** Update rule for CLUM
A CLUM sprouts a PRIMARY TILLERING among itself in the next time step with probability $P_{\text{sprout}}$ and with sprouting radius $R \leq 3$.

**Rule 3:** Update rule for PRIMARY TILLERING
A PRIMARY TILLERING sprouts a SECONDARY TILLERING among itself in the next time step with probability $p_{sprout}$ and with sprouting radius $R \leq 3$.

Rule 4: Update rule for SECONDARY TILLERING

A SECONDARY TILLERING sprouts a TERTIARY TILLERING among itself in the next time with probability $p_{sprout}$ and with sprouting radius $R \leq 3$.

3.2.3. Used parameters, meaning and values. Table 1 shows all parameters used in our model, including its meaning and values. The chosen parameters are based on our experimental data; however, some are chosen to obtain quantitative results that agree with the dynamics obtained in field experiments.

4. Simulation results and discussion

An example of typical snapshots of spatial growth of an individual rice over time simulated by our simulation are presented. We show the initial configuration of a 25-days-old rice in SEEDLING state in a paddy field (figure 1a). Subsequently, the rice grew into a CLUMP stage at 37 days old (figure 1b). The CLUMP begins to sprout PRIMARY TILLERING shoots when it is 39 (figure 1c). The PRIMARY TILLERING shoot begins to sprout SECONDARY TILLERING shoots at 43 days old (figure 1d). The SECONDARY TILLERING produces a TERTIARY TILLERING when it is 49 day old. Finally, the rice reaches the last day of its tillering state at 103 days old shown in figure 1f.

Figure 1. An example of typical snapshots of growth dynamics of an individual rice at different time steps (planting condition T1) simulated by our model. (a)-(f) show the changes in the states and spatial distribution of an individual rice at Day 1, 13, 15, 19, 25, 81 in ours corresponding to rice at 25, 37, 39, 43, 49 and 103 days old, respectively.

Figure 2 shows the tillering dynamics of an individual rice in various planting conditions obtained by our model comparison along with the results from field experiments at $R^2 = 98\%$. The simulation results are averaged over 2,000 runs, along with the simulation time in the unit of day corresponding to 79 days in real life (from March 10 to May 28, 2016 equivalent to 25-103 days old of rice growth). The simulation results show that our CA model could represent dynamics of rice growth during the vegetative growth phase of an individual rice grown under SRI for various planting conditions, based on our assigned conditions and parameters. This is consistent to our assumption that CA might be used as an alternative software tool to describe the dynamics of rice growth and might be able to predict rice yield in the future.
Based on the simulation results, it is found that the typical dynamics of the vegetative growth phase of  *Chai Nat 1* grown in sandy soil during dry season takes approximately 2.63 months (79 days). After being transplanted into the plot at 25 days old, the seedlings begin tillering when reaching 35 days old and then reduces its tillering rate after 60 days. This feature of the tillering agree with S-curve which could be divided into two phases. The first phase is characterized by an exponential ranging from Day 11 to 35 in our simulation corresponding to Mar 20 to Apr 13 in real life, while the second phase shows saturation growth behaviors like power law distribution ranging from Day 36 to 79, corresponding to Apr 14 to May 28.

**Figure 2.** Comparison of data simulated by our model and data obtained from field experiments. (a) conditions of planting with one plant per hill transplanting with the spacing density 25 x 25 cm$^2$ (T1), 30 x 30 cm$^2$ (T4), 40 x 40 cm$^2$ (T7), and 50 x 50 cm$^2$ (T10), respectively; (b) conditions when two plants per hill transplanting with 25 x 25 cm$^2$ (T2), 30 x 30 cm$^2$ (T5), 40 x 40 cm$^2$ (T8), and 50 x 50 cm$^2$ (T11), respectively; (c) conditions of three plants per hill transplanting with 25 x 25 cm$^2$ (T3), 30 x 30 cm$^2$ (T6), 40 x 40 cm$^2$ (T9), and 50 x 50 cm$^2$ (T12), respectively.

Figure 3 and 4 show the expansion of the S-curve graph of rice tillering dynamics. Figure 3 shows the dynamics of rice tillering during the exponential growth phase (called, Phase 1 in this paper). Exponential progression is used to obtain a best-fitting curve for Day 11 to Day 35 in our simulation corresponding to 25 days in real life. Dynamics of rice during this phase exhibit an exponential growth by $y = ae^{\alpha t}$; where $a$ is an initial rice population and $\alpha$ is rice growth rate (at 95% confidence interval). Given the exponential increase, $2a(0) = a(0)e^{\alpha t_d}$, and hence the rice growth doubling time is $t_d = \frac{\ln 2}{\alpha}$.

Figure 3a shows that the rice growth rate when one plant per hill combined with 25 x 25 cm$^2$ (T1) is 0.112 ($t_d \approx 6.17$ days), and those with 30 x 30 cm$^2$ (T4) and 40 x 40 cm$^2$ (T7), are very similar, 0.117 ($t_d \approx 5.93$ days) and 0.115 ($t_d \approx 6.01$ days) respectively. The best condition among those
conditions is when one plant per hill combined with 50 x 50 cm$^2$ (T10) which is the rice growth rate equal to 0.12 with doubling time $t_d \approx 5.78$ days.

While planting with two plants per hill (figure 3b) shows the growth rates of 0.096 ($t_d \approx 7.24$ days), 0.092 ($t_d \approx 7.53$ days), and 0.095 ($t_d \approx 7.32$ days) in growth areas of 25 x 25 cm$^2$ (T2), 30 x 30 cm$^2$ (T5), and 40 x 40 cm$^2$ (T8) respectively. We have found that rice growth rates of these three conditions are very similar. Unlike other conditions, the growth rate of rice grown at 50 x 50 cm$^2$ (T11) is 0.111, and doubling time $t_d \approx 6.26$ days in real life.

![Figure 3](image_url)

**Figure 3.** Dynamics of rice tillering with respect to time of days during the exponential growth phase simulated by our model when the spacing density are varied. (a) is planting conditions when the planting density is one plant per hill transplanting with 25 x 25 cm$^2$ (T1), 30 x 30 cm$^2$ (T4), 40 x 40 cm$^2$ (T7), and 50 x 50 cm$^2$ (T10), respectively; (b) is when the planting density is two plants per hill transplanting with 25 x 25 cm$^2$ (T2), 30 x 30 cm$^2$ (T5), 40 x 40 cm$^2$ (T8), and 50 x 50 cm$^2$ (T11), respectively; (c) is when the planting density is three plants per hill transplanting with 25 x 25 cm$^2$ (T3), 30 x 30 cm$^2$ (T6), 40 x 40 cm$^2$ (T9), and 50 x 50 cm$^2$ (T12), respectively.

Furthermore, plantation with three plants per hill has growth rate of 0.080, 0.082, 0.087, and 0.093 with doubling time $t_d \approx 8.66, 8.47, 8.01, \text{ and } 7.47$ days, respectively (figure 3c). These reveal similar growth rates of planting three plants per hill with 25 x 25 cm$^2$ (T3) and 30 x 30 cm$^2$ (T6). However, the growth rate is increased when rice plants are grown in 40 x 40 cm$^2$ (T9) spacing density or larger. The highest growth rate is when the rice was planted in 50 x 50 cm$^2$ (T12). Therefore, the fastest tillering during this exponential growth phase is the combination of planting with one plant per hill and 50 x 50 cm$^2$ spacing density (T10) ($t_d \approx 5.78$ days).

Although planting with one plant per hill would accelerate tillering process, when we considered the number of tillers of the rice at the end of Phase 1, we found that plantations with one plant per hill
caused very low tillering while the combination between planting with two plants per hill mixed with 50 x 50 cm$^2$ spacing density (T11) resulted in the maximum number of tillers, 29 tillers per hill. Following with the combination between planting with three plants per hill with 50 x 50 cm$^2$ spacing density, and those with 40 x 40 cm$^2$ spacing density result 26 and 22 tillers per hill respectively. Whereas the number of tillers when planting with three plants per hill transplanting with 25 x 25 cm$^2$ and 30 x 30 cm$^2$ are not different from those when planting with two plants per hill with 25 x 25 cm$^2$ to 40 x 40 cm$^2$, and those with one plant per hill, which resulted 15-20 tillers per hill as well.

Figure 4. Dynamics of rice tillering during the saturation growth phase simulated by our CA model when the spacing density are varied. (a) Initial planting density of one plant per hill transplanting with 25 x 25 cm$^2$ (T1), 30 x 30 cm$^2$ (T4), 40 x 40 cm$^2$ (T7), and 50 x 50 cm$^2$ (T10), respectively; (b) Two plants per hill transplanting with 25 x 25 cm$^2$ (T2), 30 x 30 cm$^2$ (T5), 40 x 40 cm$^2$ (T8), and 50 x 50 cm$^2$ (T11), respectively; (c) Three plants per hill transplanting with 25 x 25 cm$^2$ (T3), 30 x 30 cm$^2$ (T6), 40 x 40 cm$^2$ (T9), and 50 x 50 cm$^2$ (T12), respectively.

Figure 4 shows dynamics of rice tillering during the saturation growth phase, so called Phase 2. The power law behavior is used to obtain the best-fitting curve for Day 36 to Day 79 of the simulation corresponding to 54 days in real life. Dynamics of rice during this phase has a power law behavior by $y = ax^b + c$; where $a$ is a growth coefficient, $b$ is law’s exponent, and $c$ is a deviation term, given $\log(y - c) = b \log x + \log a$, and hence rice growth rate is $b$.

We found that rice growth rates of one plant per hill combined with 25 x 25 cm$^2$ (T1), 30 x 30 cm$^2$ (T4), 40 x 40 cm$^2$ (T7), and 50 x 50 cm$^2$ (T10) are 0.368, 0.329, 0.340, and 0.316, respectively. Therefore, the growth rate of rice reached maximum when rice was planted in 25 x 25 cm$^2$ spacing density. In contrast, the rate is lower in 50 x 50 cm$^2$ spacing density. When we consider the end of Phase 2, there are similar numbers of tillers when planting with one plant per hill for the spacing size 30 x 30 cm$^2$ (T4; 38 tillers) and 40 x 40 cm$^2$ (T7; 38 tillers). Planting at 50 x 50 cm$^2$ (T10; 43 tillers) gave the largest number of tillers whereas 25 x 25 cm$^2$ (T1; 34 tillers) resulted in the lowest number.
Growing two plants per hill resulted in the rice growth rates of 0.347 (T2), 0.379 (T5), 0.386 (T8), and 0.206 (T11). The rice growth rate reached maximum at 40 x 40 cm² spacing density, and the growth rate decreased in larger space density. In contrast, when the number of tillers were considered, we found that planting with two plants per hill in the spacing sized ranging from 25 x 25 cm² to 40 x 40 cm² resulted in the similar number of tillers, whilst planting within space 50 x 50 cm² (T10; 43 tillers) results in the maximum number of tillering.

Lastly, when rice is transplanted with three plants per hill with a spacing density of 25 x 25 cm², 30 x 30 cm², 40 x 40 cm², and 50 x 50 cm², corresponding to T3, T6, T9, and T12, respectively, it is found that the rice growth rates are 0.388, 0.382, 0.342, and 0.282, respectively. These observations suggest that rice growth rate is inversely varied due to the spacing size. However, when the number of tillers is considered, we found that the number of tillers are similar in 25 x 25 cm² and 30 x 30 cm² groups, but the number of tillers is increased when the spacing density is increased, the maximum number of the tillering occurs when the rice is planted with 50 x 50 cm² spacing density.

Based on parameters appeared in the power law equation, it seems that the growth coefficient, a, might affect the number of rice tillers, y, rather than the variable of growth rate, b which is the growth coefficient is related to the number of tillers at the end of phase 1. It implies that the growth of rice during the exponential growth phase has much more effect on the number of rice tillers rather than the phase of saturation. Therefore, the most effective conditions in rice tillering during this saturation phase, are the plantation with the combination between planting with two plants per hill with 50 x 50 cm² (T11; 50 tillers), three plants per hill with 50 x 50 cm² (T12; 47 tillers), and one plant per hill with 50 x 50 cm² (T10; 50 tillers), respectively.

| Planting conditions sorted by the number of tillers during Phase 1 | Planting conditions sorted by the number of tillers during Phase 2 |
|---|---|
| T11 : 2 plants per hill at 50 x 50 cm² (29.12 tillers) | T11 : 2 plants per hill at 50 x 50 cm² (50.50 tillers) |
| T12 : 3 plants per hill at 50 x 50 cm² (25.98 tillers) | T12 : 3 plants per hill at 50 x 50 cm² (47.38 tillers) |
| T9 : 3 plants per hill at 40 x 40 cm² (22.30 tillers) | T10 : 1 plant per hill at 50 x 50 cm² (42.70 tillers) |
| T6 : 3 plants per hill at 30 x 30 cm² (19.68 tillers) | T9 : 3 plants per hill at 40 x 40 cm² (42.19 tillers) |
| T10 : 1 plant per hill at 50 x 50 cm² (19.56 tillers) | T6 : 3 plants per hill at 30 x 30 cm² (38.70 tillers) |
| T3 : 3 plants per hill at 25 x 25 cm² (18.90 tillers) | T8 : 2 plants per hill at 40 x 40 cm² (38.69 tillers) |
| T8 : 2 plants per hill at 40 x 40 cm² (18.80 tillers) | T7 : 1 plant per hill at 40 x 40 cm² (38.32 tillers) |
| T5 : 2 plants per hill at 30 x 30 cm² (18.06 tillers) | T4 : 1 plant per hill at 30 x 30 cm² (38.16 tillers) |
| T7 : 1 plant per hill at 40 x 40 cm² (17.69 tillers) | T5 : 2 plants per hill at 30 x 30 cm² (37.83 tillers) |
| T2 : 2 plants per hill at 25 x 25 cm² (17.16 tillers) | T3 : 3 plants per hill at 25 x 25 cm² (36.87 tillers) |
| T4 : 1 plant per hill at 30 x 30 cm² (16.99 tillers) | T2 : 2 plants per hill at 25 x 25 cm² (36.61 tillers) |
| T11 : 1 plant per hill at 25 x 25 cm² (14.83 tillers) | T1 : 1 plant per hill at 25 x 25 cm² (34.37 tillers) |

Figure 5. Planting conditions sorted by the number of tillers for each growth phase.

Figure 5 summary of the amount of rice collected from various planting conditions sorted by the highest number of tillers to the lowest during Phase 1 and Phase 2. It reveals the dynamics of rice growth are varied in the different initial planting density and the initial spacing density conditions. During the first phase, the dynamics is dominated by the initial planting density, while the rice growth during second phase is dominated by initial spacing density.

The best planting condition is two plants per hill grown in 50 x 50 cm² (T11) spacing density producing the highest number of rice tillers both in the first phase and the second phase. The second-best planting condition is three plants per hill grown in 50 x 50 cm² (T12). It implies that the spacing density 50 x 50 cm² might be too small for planting by three plants per hill. In other words, the initial planning density with three plants per hill is suitable for the initial space larger than 50 x 50 cm². With this an unappropriated space, rice in the T12 condition might be uncomfortable to grow including the nutrients content for each rice shoot might not be enough. The condition T11 planting with two plants per hill at 50 x 50 cm² here thus is the most optimized condition for growing the rice in this situation.
Furthermore, the sequence changes in the sector also support our hypothesis that the initial planting density is dominated in rice growth during phase 1 while the initial spacing density is dominated during phase 2 as observed by changes in planting with T10 condition that are moved up to the third outpaced of the planting condition T9 and T6 respectively while planting conditions T1, T2, and T3 reserve the top lowest three conditions in tillering during phase 2.

5. Conclusions

We developed a stochastic cellular automata model to describe dynamics of an individual rice during vegetative growth phase for various plantation conditions. The simulation results show that the typical dynamics of a vegetative growth phase of Chai Nat 1 are 2.63 months (79 days) characterized by S-curve which could be divided into two phases - an exponential growth phase and a saturation phase i.e. behavior like power law distribution. The dynamics of rice during the exponential growth phase is dominated by the initial planting density while the dynamics during saturation phase is dominated by the initial spacing density. Furthermore, to avoid the spatial limitation the simulation results also reveal that planting with one plant per hill is suitable with the initial spacing density $30 \times 30 \text{cm}^2$ or larger, two plants per hill might be suitable with the initial spacing density $40 \times 40 \text{cm}^2$ or larger, and three plants per hill is suitable with the initial spacing density larger than $50 \times 50 \text{cm}^2$.

These suggest that based on the assigned condition and parameters, our CA model could represent dynamics of rice growth during the vegetative growth phase of an individual rice grown under SRI for various planting conditions. Importantly, CA is an alternative software tool for describing the dynamics of rice and would allow prediction of rice yield in the future.

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