Prediction of Seedling Emergence and Early Growth of *Eleocharis kuroguwai* Ohwi under Elevated Temperature

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상승된 온도 조건에서 올방개(*Eleocharis kuroguwai*)의 출아 및 초기생장 예측

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ABSTRACT Field and pot experiments were conducted to investigate seedling emergence and early growth of *Eleocharis kuroguwai* panted on different dates. Non-linear regression analyses of observed data against effective accumulated temperature (EAT) with the Gompertz model showed that the Gompertz model works well in describing seedling emergence and early growth of *E. kuroguwai* regardless of planting date and soil burial depth. EATs required for 50% of the maximum seedling emergence of *E. kuroguwai* planted at 1, 3 and 5 cm soil burial depth in the pot experiment were estimated to be 54.5, 84.0 and 118.0℃, respectively, and 56.7℃ when planted at 1 cm in the field experiment. EATs required for 50% of the maximum leaf number of *E. kuroguwai* planted at 1, 3 and 5 cm soil burial depth in the pot experiment were estimated to be 213.3, 249.0 and 291.6℃, respectively, and 239.5℃ when planted at 1 cm in the field experiment. Therefore, models developed in this study thus predicted that if rotary tillage with water is made on 27 May under +2℃ elevated temperature condition, dates for 50% of the maximum seedling emergence, 5 leaf stage and 5 cm plant height of *E. kuroguwai* buried at 3 cm soil depth were predicted to be 2 June, 10 June and 12 June. These dates are 1 day earlier for the seedling emergence and 3 days earlier for the early growth as compared with current temperature condition,

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suggesting that earlier application of herbicides is required for effective control of *E. kuroguwai*.

Key words: climate change; *Eleocharis kuroguwai*; growth prediction; modeling; seedling emergence.

INTRODUCTION

Atmospheric temperature increased by 0.74℃ during last century and will increase additional 1.4 - 4.0℃ in this century (IPCC 2007). Increasing temperature will affect not only crops but also weeds. Many studies have been conducted to investigate eco-physiological effects of elevated temperature and CO_2 on crops (e.g. Jones *et al.* 2003; Tubiello *et al.* 2002). However, not many studies have been conducted on weeds although increasing temperature is expected to affect weed eco-physiology including seedling emergence and growth of weeds and their competition with crops, which will therefore affect weed management.

Eleocharis kuroguwai Ohwi (water chestnut) is one of the most important weed species in rice cultivation of Korea, dominant in machine transplanted paddy fields (Chae and Guh 1999) and direct water-sown rice field (Kim and Pyon 1998). *E. kuroguwai* has also been reported to be the most important perennial weed species in temperate rice fields (Kim 1983) including Japan (Takabayashi 1988). Additionally, its close relative species, *E. dulcis*, has been reported as a weed in more than 45 countries worldwide (Holm 1997). The phenology of these species, erect tufted, slender and cylindric culms, takes advantage in light competition over rice. These species appear to be strong root competitors in paddy fields. For example, *E. dulcis* reduced the level of nitrate and ammonium nitrogen sufficiently, calculating that the plants removed 108, 7, 1000, 245 and 140 kg ha^{-1} of N, P, K, Ca and Mg, respectively (McCord and Loyacano 1978). Their competitive abilities over rice result in significant yield penalties in rice production in many Asian countries, causing 25~30% yield loss at 200 g of *E. kuroguwai* above ground biomass.

Leaf stage of a target weed is an important indicator in weed management as herbicide application timing is often guided based on weed leaf stage. If we could expect a specific leaf stage of the target weed, we can make a right decision for herbicide application in advance. Seedling emergence and early growth is affected by various factors, but air temperature is the most important factor (e.g. Steinbauer and Grigsby 1957; Pyon *et al.* 1990). Many studies of improving relationship between leaf stage and effective accumulated temperature (EAT) were conducted to predict leaf stage (e.g. Morita 2000; Moon *et al.* 2004). EATs for 2 leaf stage of *Echinochloa crus-galli* and *Aneilema keisak* were estimated to be 127~128℃ and 110~120℃, respectively (Moon *et al.* 2004). However, no studies regarding prediction of seedling emergence and early growth of *E. kuroguwai* in respect to climate change has been conducted. If such models using EAT can be developed, they can be utilized to predict seedling emergence and early growth under various temperature scenarios, so that timing for weed control can be advised appropriately.

Therefore, this study was conducted to predict seedling emergence and early growth using a mathematical model based on EATs in order to advice appropriate timing for *E. kuroguwai* control in Korea based on IPCC's A1B scenario.

MATERIALS AND METHODS

Data generation

An outdoor pot experiment was conducted at the experimental farm station of Seoul National University, Suwon, Korea in 2009. Each 5 *E. kuroguwai* tubers were planted at 1000 cm^2 pot in soil depths of 1, 3 and 5 cm on different dates, 6, 13, 20 and 27 June 2009 to give different temperature regimes. Pots were placed ambient temperature condition and the water depth was maintained to be 3 ± 1 cm by regular top irrigation. Number of emerged seedlings, plant height and number of leaves were daily recorded until 34 days after each planting. The experiment was consisted of three replicates in a completely randomized design.

A field experiment was also conducted at a paddy field of RDA experimental farm station, Suwon, Korea in 2002. Each 25 tubers of *E. kuroguwai* were planted in the soil depth of 1 cm after rotary tillage with water on different dates, 7, 17, and 27 May 2002 to give different temperature regimes. Number of emerged seedlings, number of leaf and plant height were recorded every 3 or 4 days after transplanting until 34 days after each planting. The experiment was consisted of three replicates in a completely randomized design.

Model development and prediction

The seedling emergence model describes mathematically the emergence pattern of seedlings, which is expressed as the time course of cumulative emergence. Although several models have been developed, the simplest and widely used (e.g. Cussans *et al.* 1996; Kim *et al.* 2006) model is Gompertz (1825) curve,

$$Y_{(T)} = \frac{C}{e^{e^{-B(T-M)}}} \quad (1)$$

where ***Y*** is the accumulated seedling emergence at days (***T***) after planting or sowing. ***C*** is the maximum seedling emergence, ***B*** is the rate of increase of seedling emergence once it is initiated and ***M*** is a time lag to reach 50% of the maximum seedling emergence. In this case, parameters will be affected by air temperature, particularly parameters ***M***. Therefore, the later the planting date, the earlier the seedling will be as later planting will allow planted tubers or sown seeds to be exposed to higher temperature in a given period of time than earlier planting. However, EAT is used instead of days after sowing as an independent variable, parameters may be no or less affected by planting date. Therefore equation 1 can be rewritten as follows by using EAT (***t***),

$$Y_{(t)} = \frac{C}{e^{e^{-B(t-M)}}} \quad (2)$$

where ***M*** is a EAT required to reach 50% of the maximum seedling emergence.

Daily effective temperature was obtained by subtracting the base temperature of 10℃ from daily mean temperature measured at Suwon Regional Meteorological Office in Suwon during the period of each experiment and then accumulated to get EAT.

For leaf stage and plant height, the Gompertz model (equation 2) was also used to describe early growth of *E. kuroguwai* planted on different dates and soil depths with increasing EAT.

Statistical analysis

Non-linear regression analysis was conducted to fit the Gompertz model to observed data. All the statistical analyses were conducted by using Genstat 5 release 4.1 (Genstat 5 Committee 1997).

RESULTS AND DISCUSSION

Seedling emergence

When seedling emergence data were plotted against days after planting, our assumption that the later the planting of *E. kuroguwai*, the earlier its seedling emergence is, was clearly proved (Fig. 1). When seedling emergence was modelled with the Gompertz model by plotting seedling emergence versus days after planting, parameters, particularly ***M*** (a time lag to reach 50% of the maximum seedling emergence), changed with planting date (Fig. 1), suggesting that seedling emergence model cannot be used for different temperature condition. Therefore, instead of days after planting as an independent variable, EAT was used to model seedling emergence of *E. kuroguwai* planted on different dates. Seedling emergence of *E. kuroguwai* planted in the same soil depth plotted against EAT was well explained by the Gompertz model with less changes in the parameter ***m*** (EAT required to 50% of the maximum seedling emergence) with panting date than that plotted against days after planting (Fig. 2). EATs required for 50% of the maximum seedling emergence of *E. kuroguwai* planted at 1, 3 and 5 cm soil burial depth were estimated to be 54.5, 84.0, and 118.0℃, respectively, in the pot experiment in 2009. In the field experiment in 2002, the EAT of *E. kuroguwai* planted at 1 cm was 56.7℃, which is very close to the pot experiment with 54.5℃, suggesting that the seedling emergence model developed by using the Gompertz model and EAT can be utilized to predict seedling emergence of *E. kuroguwai* under different temperature conditions.

Unlikely the parameter ***m***, the maximum seedling

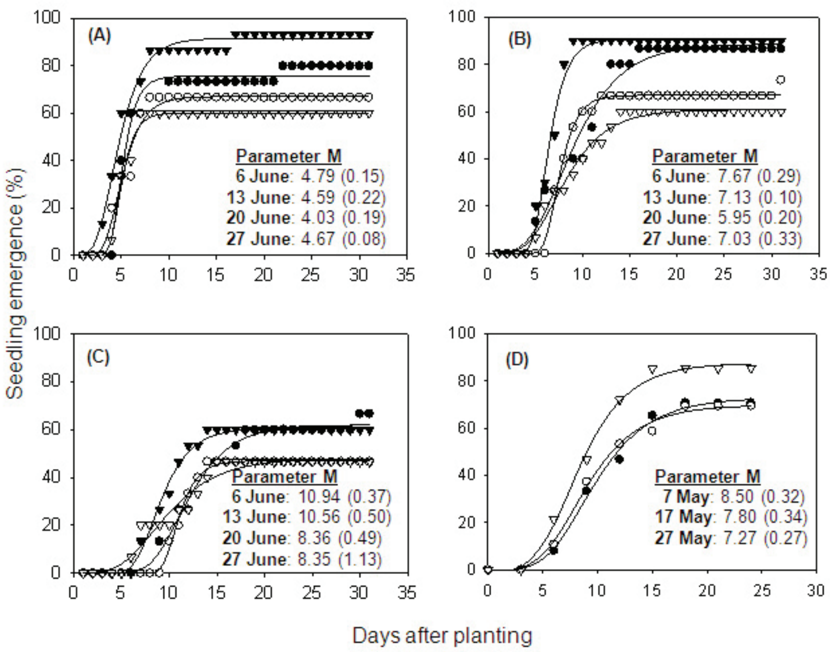

Fig. 1 Seedling emergence (%) of *Eleocharis kuroguwai* planted in outdoor pots on 6 (●), 13 (○), 20 (▼) and 27 (▽) June 2009 at different soil depths, 1 (A), 3 (B) and 5 cm (C), and panted in the paddy field (D) on 7 (●), 17 (○) and 27 (▽) May 2002. The continuous lines are fitted seedling emergence versus days after planting by using the Gompertz model and their parameter estimates. The parameter ***M*** indicates a time lag to reach 50% of the maximum seedling emergence.

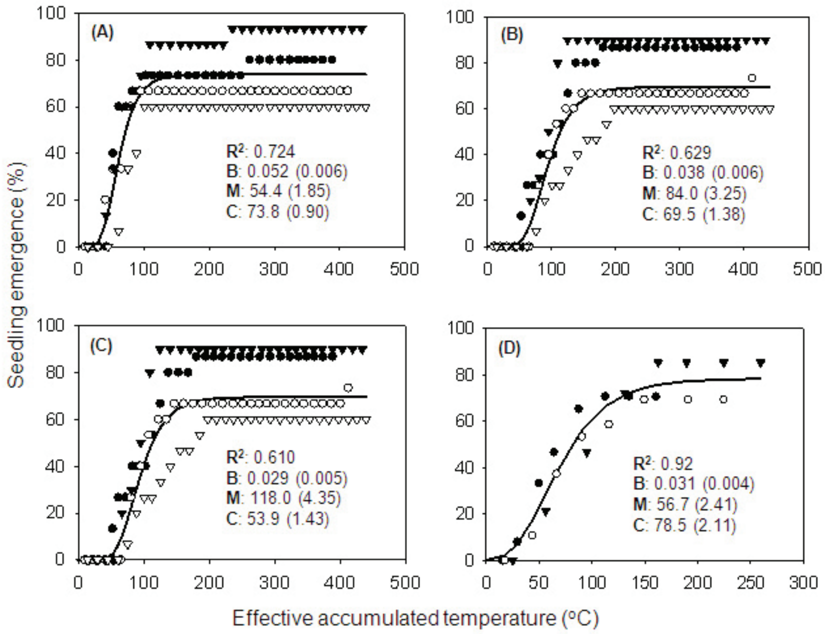

Fig. 2 Seedling emergence (%) of *Eleocharis kuroguwai* planted in outdoor pots on 6 (●), 13 (○), 20 (▼) and 27 (▽) June 2009 at different soil depths, 1 (A), 3 (B) and 5 cm (C), and panted in the paddy field (D) on 7 (●), 17 (○) and 27 (▼) May 2002. The continuous lines are fitted seedling emergence by using the Gompertz model and their parameter estimates, whose standard errors are in parentheses. The parameter ***M*** indicates an EAT required to reach 50% of the maximum seedling emergence.

emergence (***C***) and the emergence rate (***B***) were very much affected by planting date (Fig. 1 and Fig. 2). The maximum seedling emergence was maintained relatively high up to the second planting, but significantly decreased after the third planting on 20 June. The emergence rate was also decreased when planted later timing. Such decreases in the maximum seedling emergence and the emergence rate may be due to reduced viability of tubers stored in the cold chamber maintained at 4℃ before planting. The longer the period of storage, the lower the tuber viability is.

Number of leaf

Leaf number was also fitted to the Gompertz model with EAT to model early leaf development of *E. kuroguwai* planted on different dates. The Gompertz model also well described the early leaf development of *E. kuroguwai* with EAT. The parameter ***m*** (EATs for 50% of the maximum leaf number) were estimated to be 213.3, 249.0 and 291.6 ℃ at 1, 3 and 5 cm soil burial depth, respectively, in the pot experiment, and 239.5℃ in the field experiment (Fig. 3). Based on the model and its parameter estimates, EAT required for a specific leaf stage of *E. kuroguwai* can be estimated. For example, EATs required for 5 leaf stage were estimated to be 155.3, 188.5, and 215.5℃ at 1, 3 and 5 cm soil burial depth, respectively. These estimated EAT can be used to predict dates reaching the specific leaf stage under various temperature conditions.

Plant height

As an indicator of plant growth, plant height of *E. kuroguwai* was also measured and plotted against EAT (Fig. 4). Plant height versus EAT was

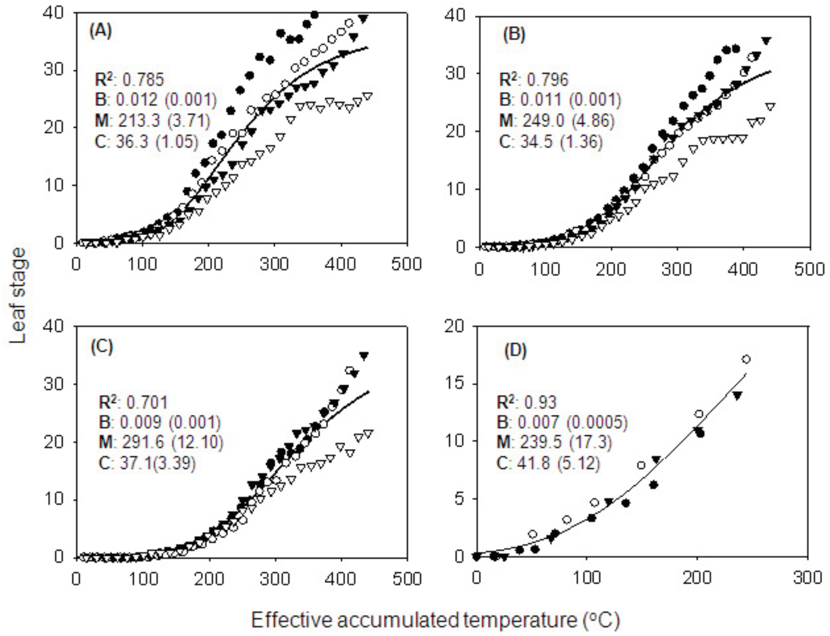

Fig. 3 Leaf stage of *Eleocharis kuroguwai* planted in outdoor pots on 6 (●), 13 (○), 20 (▼) and 27 (▽) June 2009 at different soil depths, 1 (A), 3 (B) and 5 cm (C), and panted in the paddy field (D) on 7 (●), 17 (○) and 27 (▼) May 2002. The continuous lines are fitted leaf stage by using the Gompertz model and their parameter estimates, whose standard errors are in parentheses. The parameter ***M*** indicates an EAT required to reach 50% of the maximum leaf stage.

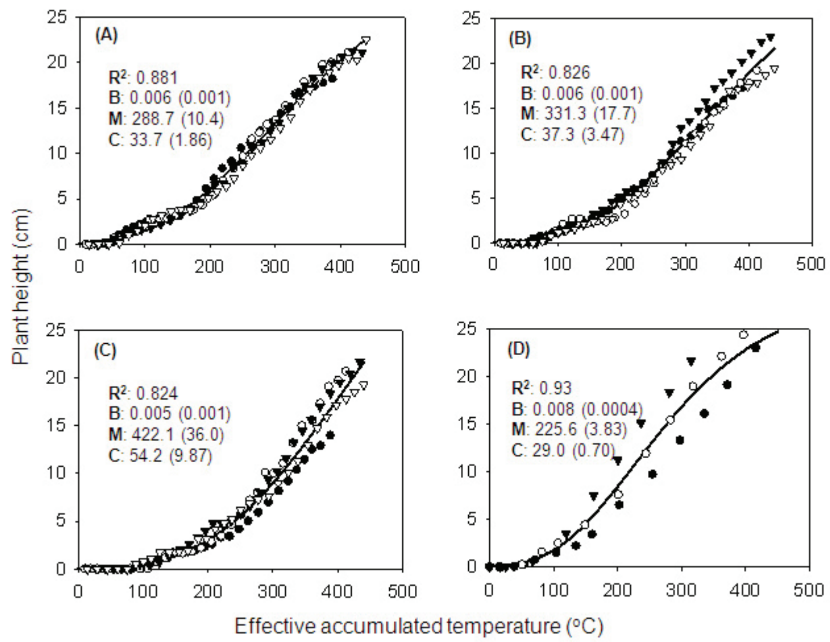

Fig. 4 Plant height (cm) of *Eleocharis kuroguwai* planted in outdoor pots on 6 (●), 13 (○), 20 (▼) and 27 (▽) June 2009 at different soil depths, 1 (A), 3 (B) and 5 cm (C), and panted in the paddy field (D) on 7 (●), 17 (○) and 27 (▼) May 2002. The continuous lines are fitted plant height by using the Gompertz model and their parameter estimates, whose standard errors are in parentheses. The parameter ***M*** indicates an EAT required to reach 50% of the maximum plant height.

modelled with the Gompertz model, which well described the plant growth of *E. kuroguwai* in its plant height. The parameter ***m*** (EATs for 50% of the maximum plant height) were estimated to be 288.7, 331.3 and 422.1℃ at 1, 3 and 5 cm soil burial depth, respectively, in the pot experiment, and 225.6℃ in the field experiment (Fig. 4). Based on the model and its parameter estimates, EAT required to reach a specific plant height of *E. kuroguwai* can be estimated. For example, EATs required for 5 cm plant height were estimated to be 181.9, 207.4 and 240.7℃ at 1, 3 and 5 cm soil burial depth, respectively. These estimated EAT can be used to predict dates reaching the specific plant height under various temperature conditions.

Prediction of seedling emergence and early growth under elevated temperature

By using the models for seedling emergence, number of leaf, and plant height of *E. kuroguwai*, dates reaching 50% of the maximum seedling emergence, 5 leaf stage and 5 cm plant height were estimated under current and +2℃ elevated temperature conditions if rotary tillage with water is made on 27 May, which can be regarded as a date of planting *E. kuroguwai* tubers (Table 1). Under +2℃ elevated temperature condition, dates for 50% of the maximum seedling emergence were estimated to be 31 May, 2 June and 5 June for tubers placed on 1, 3, and 5 cm soil depth, respectively, while those were 1 June, 3 June and 7 June, respectively, indicating 1-2 days earlier seedling emergence under +2℃ elevated temperature as compared with current temperature (Table 1). Dates for 5 leaf stage under current temperature condition were estimated to be 10 ~ 15 June, which is the timing for mid one-shot herbicide application. Under +2℃ elevated temperature, they were estimated to be 8 - 13 June, about 2 ~ 3 days earlier than current temperature condition and equivalent to the timing for early-mid one-shot herbicide application. Dates for 5 cm plant height were also estimated to be 2 ~ 3 days earlier under +2℃ elevated temperature as compared with current temperature condition. Therefore, these results suggest that herbicide application should be made earlier under elevated temperature condition in the future as seedling emergence and early growth of *E. kuroguwai* are facilitated.

Table 1. Estimated dates for 50% maximum seedling emergence and 5 leaf stage of *E. kuroguwai* under current air temperature and +2℃ elevated temperature conditions.

Predicted date for	Temperature	Tuber burial depth (cm)		
		1	3	5
50% maximum seedling emergence	Present	1 June	3 June	7 June
	+2℃	31 May	2 June	5 June
	Difference*	▽1	▽1	▽2
5 leaf stage	Present	10 June	13 June	15 June
	+2℃	8 June	10 June	13 June
	Difference	▽2	▽3	▽2
5 cm plant height	Present	12 June	15 June	17 June
	+2℃	10 June	12 June	15 June
	Difference	▽2	▽3	▽2

* Difference indicates difference in predicted date between present and +2℃ elevated temperature.

Global warming is comprised of elevated temperature and CO_2 concentration. However, our study only dealt with elevated temperature. If elevated CO_2 is also considered, growth responses of *E. kuroguwai* will be affected, while its seedling emergence may not be affected as germination and seedling emergence are mainly determined by temperature but not by CO_2. Elevated temperature and CO_2 may also affect not only seedling emergence and growth of *E. kuroguwai*, but also herbicide activity. In general, herbicide activity improves with increasing temperature (e.g. Ichizen *et al.* 1996) although there are some exemptions (e.g. Lee *et al.* 2006). As shown in Table 1, herbicide application timing needs to be earlier under elevated temperature. However, earlier herbicide application may cause damage on rice as herbicide application timing is determined based on not only herbicide efficacy against weeds but also crop safety.

In conclusion, our work clearly demonstrates that the Gompertz model well describes seedling emergence and early growth of *E. kuroguwai* plotted against EAT when planted different dates to give different temperature conditions. The models developed were successfully applied to predict dates for seedling emergence and early growth under various temperature scenarios. Further works also required to investigate the effects of elevated temperature and CO_2, and early herbicide application on herbicide activity.

요 약

기온상승 조건을 부여하기 위해 재식시기를 달리하여 재식 한 올방개의 출아와 초기생장을 평가하고 이들과 유효적산온도간의 관계를 수학적 모델로 해석하기 위한 포트 및 포장평가를 수행하였다. Gompertz 모델을 이용하여 이들의 관계를 비선형회귀로 분석한 결과, 파종일자 및 재식 토양심도에 상관없이 유효적산온도로 누적출아율 및 초기생장을 양호하게 설명하였다. 올방개의 최대 출아율의 50% 도달에 필요한 유효적산온도는 올방개 괴경 재식심도 1, 3 및 5 cm에서 54.5, 84.0 및 118.0℃이었으며 5엽기에 이르는데 필요한 유효적산온도는 각각 155.3, 188.5 및 215.5℃이었다. 본 연구에서 개발된 모델식을 이용하여 계산한 결과 평균기온이 2℃ 상승한 조건에서 올방개의 50 % 출아는 심도에 따라 약 1 - 2일 빨라지고, 5엽기에 도달하는 날짜도 약 2 - 3일 빨라질 것으로 예측되었다. 따라서 2℃ 기온상승 조건에서 올방개를 효과적으로 방제하기 위해서는 현재의 제초제 처리시기보다 약 2 - 3일 빨라져야 할 것으로 판단된다.

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