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CHANGE OF THRESHOLD VELOCITY FOR GRAVEL MOVEMENT BY RUNNER EXPANSION AND GROWTH OF *Phragmites japonica* ON A GRAVEL BAR: MODELING APPROACH

By

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SYNOPSIS

Fundamental growth characteristics of *Phragmites japonica* growing on a gravel-bed river bar were investigated in the midstream of the Arakawa River, Japan. The breaking strength of runners of *P. japonica* was measured by a push-pull gauge, and their seasonal expansion characteristics were investigated quantitatively. The length of a runner was found to be closely related to the cumulative shoot height of the parent colony of the runner. The newly formed colony on a runner had enough strength to withstand velocities higher than that necessary for the initiation of gravel movement. This indicates that the lateral distribution and seasonal development of the colony play very important role in flow resistance. A dynamic growth model of *P. japonica* was formulated using the lateral enlargement characteristics of the runner. The friction velocity was calculated by the lateral biomass distribution considering the momentum equation including the drag force by the plant. The analysis shows that the shear friction velocity affected by plants was much lower than the critical shear friction velocity of the bed material after 4-5 years of colonization.

INTRODUCTION

The effects of vegetation on resistance to river flow, flow discharge and water depth has become one of the major concerns of river engineers, and many experiments in water flume and numerical analyses have been conducted (Kouwen *et al*, (1); Tsujimoto et al. (2); Righetti and Armanini (3); James et al. (4)). In particular, the importance of plant density and vegetation structures that change the drag force to flow has been demonstrated in the evaluation of shear friction (Musick et al. (5)) and bulk roughness characteristics (Nepf (6)). In addition to the effects on the flow, the decrease of a gravel bed bar by the colonization of monospecific or invasive plants has become one of the serious problems in the midstream of Japanese rivers because such plants have some possibilities to reduce the biodiversity in a river (Matsumoto et al. (7)).

Phragmites japonica, one of the important domestic plants in gravel-bed rivers, sometimes dominates the gravel bar of a river. In particular, changes in land use and decreases in the bed-load supply (Kondolf et al. (8)) decreases the flood disturbances to the plants. Furthermore, this accelerates the change of vegetation in rivers, i.e., from perennial plants to trees.

Sand or gravel movement is affected by the existence of plants, and the sand or gravel movement itself affects the growth of plants (Suzuki and Numata (9)). The interaction between plant growth and sand accumulation is important, but little quantitative knowledge about the relationship is known. It is very important to evaluate the expansion process and its effect on the shear friction around the plants. The horizontal enlargement mechanism of *P. japonica* is especially important because its enlargement process is affected by flooding. Monitoring and predicting the effects of long-term geological change due to a perennial plant requires models and relationships predictive of the influence of vegetation.

Many bio-energy analyses based on the carbon (C) budgets have been conducted recently for emergent macrophytes (Asaeda & Karunaratne (10), Tanaka et al. (11), (12)), submerged macrophytes (Asaeda & Bon (13)), and mangrove trees. These studies focused on photosynthesis, respiration, mortality, and translocation in aboveground and belowground organs and can be applied to the perennial plant *P. japonica*.

Therefore, this study is concerned with the phenology of *P. japonica* and formulates a differential equation based on C budget. Field observations necessary to observe the seasonal dynamics were made in the Arakawa River, Japan. We analyzed the change of threshold velocity for gravel movement affected by the long-term growth of *P. japonica* using the model.

MATERIALS AND METHODS

Site and species characteristics

Field experiments were conducted at a stand of *Phragmites japonica* at a gravel bed bar in the Arakawa River in Saitama Prefecture, Japan (36° 8' N and 139°22'E). The gravel bed bar, about 1000 m long and 300 m wide, is shown in Fig. 1. The gravel size varied from sand to cobbles about 20 cm in maximum diameter from the gravel surface to 50 cm depth in the bed, where the average diameter, d_{50}, was about 1 cm. The total nitrogen (TN) concentration in the substrate ranged 0.029-0.066 $\mathrm{mgg^{-1}}$.

One of the *P. japonica* stands, 20 m in length streamwise and 7 m in width, was selected for the observation (Fig. 1). The plants growing in the gravel bar were mainly *P. japonica* and *Eragrosits curvula*. The *P. japonica* habitat was at the fringe of the bar, and it extended runners (organs for horizontal expansion) to a rather high land area that was partially covered by *E. curvula*. The *P. japonica* strategy is to expand habitat by extending runners and sprouting new shoots at about 40cm distances on the runner from late April to early July. The colonies grow larger each year by means of the runner expansion system. The gravel bar is supposed to be stabilized by the plant existence. The runner length was more than 10 m in maximum, and the plant density was high at the center of the stands, where the colony and runners were not easily recognized. Hereafter, we refer to the dense stands as DS, which are thought to occur more than 3 years after colonization.

Field measurement of P. japonica growth

Field measurements were conducted from day 112 (21 April 2004) to day 386 (20 January 2005), where the day represents the date that starts from 1st January 2004 as 'day 1' in this study. There was no flood to the vegetated zone during the investigated season. Aboveground and belowground specimens were collected for each organ. The number of runners was counted, and shoot density was calculated; in particular, the length and biomass of the runners were measured during their growth. The samplings were taken in each colony with runners; at the same time, soil samples about 30 cm deep were excavated to extract rhizomes and roots. After all the soil had been washed off with pressurized water, the remaining rhizomes and roots were immediately dried at 90 °C more than 48 hours until they became a constant weight. At least three samples were taken for analyzing average value and standard deviation. The samplings and biomass measurements were taken from day 112 to day 288 (9 times). In this study, the colonies and runners were classified into groups of 6 and 3, respectively.

Fig. 2 shows the definition of the colonies and the runners. For the measurement of runner length, five runners in each R2-1 and R3-1 type runner were selected at day 127 and the observation was continued 10 times until day 197 when the runner length was the same with that at day 188. The shoot height was measured for the colony (C3, C3-2-A) on the observed runner at day 197. To clarify the relationship between shoot height and runner length, additional measurements were taken at day 220 for ten C3-2-A colonies. Sampling of the plants was also taken to investigate the seasonal change in each organ for C3 and C3-2-A colonies.

Measurement of colony and runner strength

The strength of runners and colonies was measured by a push-pull gauge (Aikoh 9550A) for C2-1 colonies on the R2-1 runner and C3-1 colonies on the R3-1 runner. The point for pushing the runner was the center of two-linked colonies, but when the node of the stem was at the center, the point moved 1 cm from the center. The threshold force for colony removal was found to be just the half the force necessary to remove the colony. The threshold value for runner strength was assumed

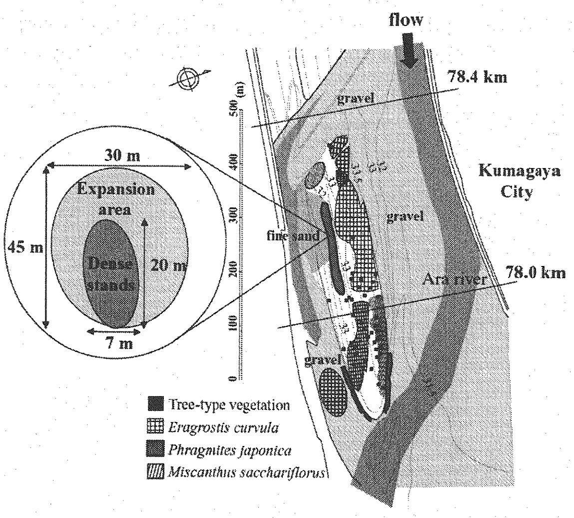
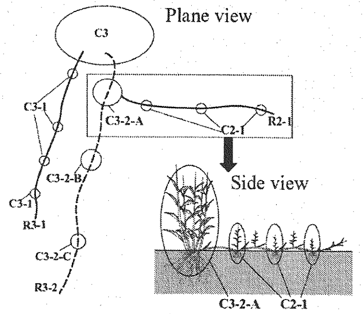


Fig. 1 Field observation site in the Arakawa River



Notation	Explanation
C3	Older than 3 years, dense stands=DS
Rn-m	m-year-old runner from n-year-old colony (n=2 or 3, m=1 or 2)
Cn-m	colony on the Rn-m runner
C3-2-J	C3-2 means colony on R3-2. J (=A or B or C) expresses the difference of runner ; A means the runner extended this year, B means no runner expansion this year, C denotes the last year's runner. (there was no expansion this year)

Fig. 2 Definition of the runners and colonies in *Phragmites japonica.*

to be the strength at which the runner broke when it was broken before the removal of the colony. After the tension test, the biomasses of the related runners, roots, and rhizomes were measured by the method explained in the previous section. Tension tests were conducted four times (days 148, 156, 174, and 222).

Analysis of growth dynamics

Governing equations of the biomass

The growth of a plant can be described by the application of bioenergetics to each organ (Titus et al. (14)). The scheme applied to the growth of *P. japonica* was similar to the model developed for *P. australis* (Asaeda and Karunaratne (10)) and *Typha* spp. (Tanaka et al. (12)). The biomass per unit area (0.16 m^2) of three organs (shoots, belowground organs except for runners, and runners) was separately formulated to account for the material gains and losses of each organ, and the inter-organ translocation, i.e., photosynthetic production, respiration, mortality, and material flows to form new shoots, to stock reserves in belowground organs and runners. The characteristics of each process were introduced mathematically into each term of the formulation.

The phenology of *P. japonica* is characterized by an initial heterotrophic growth stage based on the stocked rhizome reserves, followed by photosynthesized growth and senescence, similar to *P. australis* and *Typha* spp.

The governing equations for the three organs, shoots, belowground organs, and runners, respectively, are given below.

$$\frac{dB_{sht}}{dt}=P_{sht}-R_{sht}-D_{sht}+f_{sht\_I}\cdot T_{sht\_I}+f_{sht\_Ph}\cdot T_{sht\_Ph}-f_{below\_Ph}\cdot T_{below\_Ph}-f_{below\_S}\cdot T_{below\_S} \qquad (1)$$

$$\frac{dB_{below}}{dt}=-R_{below}-D_{below}-f_{sht\_I}\cdot T_{sht\_I}-f_{sht\_Ph}\cdot T_{sht\_Ph}+f_{below\_Ph}\cdot T_{below\_Ph}+f_{below\_S}\cdot T_{below\_S}-f_{run}\cdot T_{run} \qquad (2)$$

$$\frac{dB_{run}}{dt}=-R_{run}-D_{run}+f_{run}\cdot T_{run} \qquad (3)$$

where B (g/(0.16 m^2)) are biomasses and the subscripts *sht, below,* and *run* represent shoots, belowground organs (rhizomes and roots), and runners, respectively. Moreover, subscripts_*I*, _*Ph,* and _*S* denote initial growing season, photosynthetic growing season, and senescent season, respectively. P, R, D, and T (g/(0.16 m^2) per day) represent photosynthesis, dark respiration, mortality, and translocation between organs, respectively. f is a fraction (1 or 0) related to the phenology (see Table 1). The energy budgets per day and per unit area (0.4×0.4 m) were set and at the same time the size of a mature colony was considered. Translocation from belowground organs to shoots or from shoots to belowground organs is assumed to be proportional to B_{below} or B_{sht}, respectively, and given as

$$T_{sht\_l} = k_{sht\_l} \cdot B_{below} \tag{4}$$

$$T_{sht\_Ph} = k_{sht\_Ph} \cdot B_{below} \tag{5}$$

$$T_{below\_Ph} = k_{below\_Ph} \cdot B_{sht} \tag{6}$$

$$T_{below\_S} = k_{below\_S} \cdot B_{sht} \tag{7}$$

$$T_{run} = k_{run} \cdot B_{below} \tag{8}$$

where k_{shtl}, k_{sht_Ph}, k_{below_Ph}, k_{below_S}, *and* k_{run} are constant fractions during the translocation period.

R and D are proportional to their biomasses (Hootsmans (15), Asaeda and Karunaratne (10)) and the mean daily temperature.

$$R_a = \beta_a \cdot \theta^{(t-20)} \cdot B_a \tag{9}$$

$$D_a = \gamma_a \cdot \theta^{(t-20)} \cdot B_a \tag{10}$$

where β_a and γ_a are the specific rates of dark respiration and mortality at 20 degrees Celsius, θ is the Arrhenius constant, superscript t is the daily average temperature, and subscript a represents shoots (*sht*), belowground organs (*below*), or runners (*run*).

Shoot photosynthesis, P_{sht}, is related to photosynthetic active radiation and age, and this relationship can be expressed by a Michaelis-Menten-type equation as,

$$P_{sht} = P_m \cdot K_{CO} \cdot K_{NP} \cdot \theta^{(t-20)} \cdot \frac{I_{par}}{K_{PAR} + I_{par}} \cdot \frac{K_{age}}{K_{age} + Age_{sht}} \cdot B_{sht} \tag{11}$$

where P_m is the maximum specific net daily photosynthesis rate of the plant top at 20 degrees Celsius in the absence of light and nutrient limitations, K_{co} is the conversion constant of carbon dioxide to ash-free dry weight (Ondok (16)), and I_{PAR} is the photosynthetically active radiation (Asaeda & Karunaratne (10)). Age_{sht} is the age of shoots from the start of growth, and K_{PAR} and K_{age} are the half saturation coefficients of photosynthetically active radiation (PAR) and age, respectively.

Modeling of daily accumulated radiation and daily average temperatures were the same as reported in the work of Tanaka et al. (11). The above differential equations were solved by using the Runge- Kutta method.

Phenology of P. japonica

The phenology of *P. japonica* in one growing season was set as shown in Fig. 3. The start day of growth, the end of the heterotrophic season, and the onset of senescence were defined with reference to the observations by Kang et al. (17) and our observations as the day of the first bud in spring, the end of the season that rhizomes decreased, and the day of maximum biomass of shoots, respectively. The start and end of runner extension were set on day 127 and day 188 according to observations, respectively. Fig. 4 shows the schematic of the growth model.

Horizontal distribution analysis

In the horizontal distribution analysis, the number of runners and their length were calculated by using the runner biomass. Directions were decided at random in the analysis. Thus, expansion to a new grid area was represented. This matter is important in this study because plant expansion affects flow resistance and the initiation of gravel movement.

The total length of runners from one colony, L_{run}, was calculated by runner biomass in the unit length, B_{run_unit}, as follows

$$L_{run} = \frac{B_{run} - \sum(B_{run\_sht} + B_{run\_below})}{B_{run\_unit}} \tag{12}$$

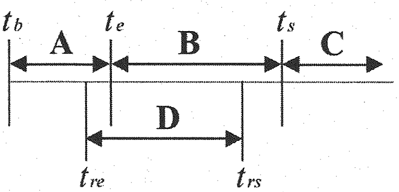
where B_{run_sht} and B_{run_below}, are the shoot biomass of a newly formed runner and belowground biomass of the runner, respectively.

The maximum horizontal rhizome length was about 10 m in this observation, thus the number of runners, N_{run}, was calculated as

$$N_{run} = INT(\frac{L_{run}}{10.0} + 1.0) \tag{13}$$

where $INT(\,)$ expresses taking the integer of the ( ) part.

The whole simulation area was set at 60×60 m and divided by a 0.4×0.4 m grid. Parameters were obtained from previously published papers (Kang et al. (17)) and field observations in the Arakawa River. Table 1 lists the parameters of the model.



A: early growing season, B: photosynthetically growing season, C: senescent season, D: growth season of runner

Start of growth	t_b=day 90
End of mobilization from rhizome to shoots and roots	t_e=day 130
Start of translocation of current photosynthate	t_s=day 240
Start of runner elongation	t_{re}=day 120
End of runner elongation	t_{rs}=day 220

Fig. 3 Phenology of *P. japonica*. ('day' means Julian day)

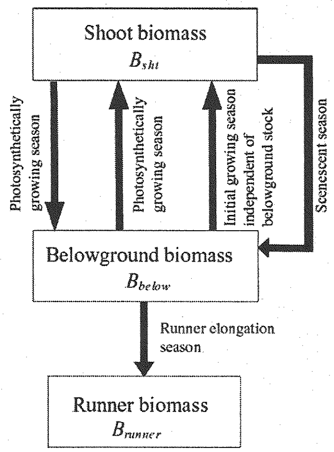


Fig. 4 Schematic of the growth model for *P. japonica*

Threshold value for colony removal and gravel movement

To compare the velocity that corresponds to the threshold value for the removal of a *P. japonica* colony and to the critical shear friction of the bed material, the relationships among the drag force by the plant, critical shear friction around the colony, and average velocity were formulated.

Change of shear friction velocity with respect to plant density of P. japonica colonies

By the aboveground biomass calculated from the growth dynamic analysis of *P. japonica*, the number of colonies per unit grid area (0.16m^2), m, was assumed to be

$$m = \frac{calculated\ shoot\ biomass\ in\ a\ grid\ area}{shoot\ biomass\ of\ a\ colony} = \frac{B_{sht}}{(specific\ mass\ of\ P.japonica) \times h\lambda\pi(\frac{D_c}{2})^2} \tag{14}$$

where D_c is the diameter of colony (m), h is the shoot height (m), and λ is the porosity of the colony.

The drag force by *P. japonica*, F, and the frontal projected area of the colony, A, were calculated as follows:

$$F = mC_d \frac{1}{2} \rho u^2 A \tag{15}$$

$$A = \lambda D_c h \sin\theta \tag{16}$$

where ρ is the mass density of water (kg/m^3), C_d, the drag coefficient, u, the average velocity of approach flow (m/s), and θ, the inclination of the plants. The drag coefficient was determined to be 0.5 on the basis of previous research (Tanaka et al. (18), Takemura & Tanaka (19), Nepf (7)).

After evaluating of the drag force, the friction velocity, u_* (m/s), was calculated as

$$\rho u_*^2 A_0 + F = \rho g H I_e \tag{17}$$

where A_0 is the area of the bed without plants (m^2), H, the water depth (m), g, the gravitational acceleration (m/s^2), and I_e, the energy slope.

Threshold value for gravel movement

Although the plant growth affects the velocity distribution and possibly changes the relationship between grain diameter and the critical friction velocity, we assume the change is not so great because our analysis targets the runner expansion area and plant density is not so high. Then, the critical friction velocity of the gravel was assumed by using Iwagaki's formula (20):

$$u_{*c}^2 = 80.9d \tag{18}$$

where u_{*c} is the critical friction velocity (cm/s) and d (cm) is the diameter of sand or gravel ($d > 0.303$ cm).

The relationship between the friction velocity and the average velocity was calculated by

$$\frac{u_*}{u} = \sqrt{\frac{gn^2}{H_R^{1/3}}} \tag{19}$$

where H_R is the hydraulic radius (m), and n is Manning's roughness coefficient (0.035 s/m$^{1/3}$ in this surveyed location (21)).

By comparing the friction velocity, u_*, in Eq.(17), and the critical friction velocity, u_{*c}, of the average diameter at the site (d_{50} = 1 cm) in Eq.(18), the rate of the area at which the mean diameter (d_{50}) does not move was determined.

Table 1 Parameter list

	Parameters		Values	Units or dimensions	Reference
k_{sht_I}	Specific transfer rate from B_{below} to B_{sht} in early growing season		0.008	-	c
k_{sht_Ph}	Specific transfer rate from B_{below} to B_{sht} in photosynthetically growing season		0.0001	-	c
k_{below_Ph}	Fraction of P_{sht} transported to B_{below} in photosynthetically growing season		0.047	-	c
k_{below_S}	Fraction of B_{sht} translocated to B_{below} in senescent season		0.015	-	c
k_{run}	Fraction of B_{below} translocated to B_{run} in runner growing season		0.067	-	c
f_{sht_I}	Fraction of the mass flux from belowground to shoot (early growing season)	: when $t_b < t < t_e$ 1、otherwise 0	0 or 1	-	c
f_{sht_Ph}	Fraction of the mass flux from belowground to shoot (photosynthetically growing season	: when $t_e < t < t_s$ 1、otherwise 0	0 or 1	-	c
f_{below_Ph}	Fraction of the mass flux from shoot to belowground (photosynthetically growing season	: when $t_e < t < t_s$ 1、otherwise 0	0 or 1	-	c
f_{below_S}	Fraction of the mass flux from shoot to belowground (senescent season)	: when $t > t_s$ 1、otherwise 0	0 or 1	-	c
f_{run}	Fraction of the mass flux from belowground to runner	: when $t_{re} < t < t_{rs}$ 1、otherwise 0	0 or 1	-	c
β_{sht}	Specific dark respiration rate of shoot at 20°C		0.007	g/g/day	a
β_{below}	Specific dark respiration rate of belowground at 20°C		0.001	g/g/day	a
β_{run}	Specific dark respiration rate of runner at 20°C		0.003	g/g/day	a
B_{run_unit}	Runner biomass in unit length		5.3	g/m	o
γ_{sht}	Specific mortality rate of shoot at 20°C	: from t_b -t_e	0.001	g/g/day	a
	Specific mortality rate of shoot at 20°C	: from t_e -t_s	0.001	g/g/day	a
	Specific mortality rate of shoot at 20°C	: after t_s	0.05	g/g/day	a
γ_{below}	Specific mortality rate of belowground at 20°C		0.0001	g/g/day	a
γ_{run}	Specific mortality rate of runner at 20°C	: from t_{re}-t_e	0.001	g/g/day	a
	Specific mortality rate of runner at 20°C	: from t_e-t_{rs}	0.005	g/g/day	a
	Specific mortality rate of runner at 20°C	: after t_{rs}	0.001	g/g/day	a
P_m	Maximum specific net daily photosynthesis rate at 20°C		0.23	gCO$_2$/g/day	a
θ	Temperature constant		1.09	-	b
K_{CO}	Conversion constant of carbon dioxide to ash-free dry weight		0.65	g/gCO$_2$	d
K_{NP}	Concentration constant of nitrogen and phosphorus		0.5	-	c
K_{age}	Harf saturation coefficient of age		125	day	o

c: calibrated, o:observed, a: Asaeda and Karunaratne(10), b:Asaeda and Bon(13), d:Ondok(16)

RESULTS AND DISCUSSION

Seasonal change of runner length and biomasses in P. japonica

Within five selected runners, the elongation of the 2, 3 runners of the R2-1, R3-1 types, respectively, was observed. They both began elongation at day 127, and it continued until day 188. The length of the observed runners ranged from about 5.2 to 9.2 m, and the maximum elongation was about 0.15-0.21 m/day. Table 2 shows the details of runner characteristics observed on day 197. This table indicates the longer length and higher elongation rate of R3-1 from DS compared with R2-1 from a colony younger than DS.

Fig. 5 shows the relationship between the total shoot height in parent colonies and the runner lengths extending from the colony. The correlation ($r^2 = 0.44$) expresses the existence of material transport from the parent colony to runners as Eq.(8).

Fig. 6 shows the seasonal changes of the observed and simulated biomasses in *P. japonica*. The shoot biomass calculated from the growth dynamic analysis of *P. japonica* agrees well with the observed data. The belowground biomasses of DS and those of all colonies on runners extended from DS were 17.7 g and 32.7 g, respectively. The simulated curves approach these values in the senescent season, but for the start of senescence, more observations are needed to increase accuracy.

Horizontal distribution analysis

Fig. 7 shows the long-term dynamics of *P. japonica* with 10 g initial belowground biomass as a point colonization at a grid, $x = 70$ and $y = 70$ (Fig. 7(a) and (b)), or lined colonization at $x = 70$, $y = 30 - 110$, with 2 grids (0.8 m) spacing (Fig. 7(c) and (d)). Fig. 7(a) and (c) show the results at day 200 after 3 years, and Fig. 7(b) and (d) show 5 years' growth, respectively. The figure shows only the biomass of colonies that extend runners, C3-2-A, even though there are two type colonies on the runner. Until three years after the start of growth, the spread of plants is slight, but the rate of increase and enlargement becomes exponential after four to five years. This indicates that the roughness increases exponentially after 4-5 years after colonization if there are no flood disturbances and damage. This also affects the bed shear friction described in Eq.(17).

Fig. 8 shows the shoot height of the colony along the distance from the center of the initially existing colony (DS). The shoot height decreases with increasing distance from the center. The shoot height distribution along the distance from DS changed with the growth stage. The simulated results represent well the observed results and, therefore, validate the accuracy of the horizontal expansion analysis within reasonable limits.

Interaction between P. japonica and gravel movement

Fig. 9 shows the relationship between the root biomass and the required force for the removal of a *P. japonica* colony. The surface area of roots is related to the root diameter, and the root biomass is correlated to the square of the root diameter. Then, the force for removal was supposed to be correlated with the (root biomass)$^{-1/2}$, by assuming that the removal force is correlated with the surface area of the roots. This finding was fairly consistent with the decision coefficient r^2=0.47. Because the root-to-shoot ratio did not change

Table 2 Characteristics of the runners, R2-1 and R3-1(day 197, numerical value shows average ± standard deviation)

	R2-1	R3-1
Shoot height (m)	0.49±0.11	0.60±0.12
Number of shoot (shoots/colony)	11.80±3.16	14.75±2.45
Length of runner (m)	6.08±1.15	8.28±0.67

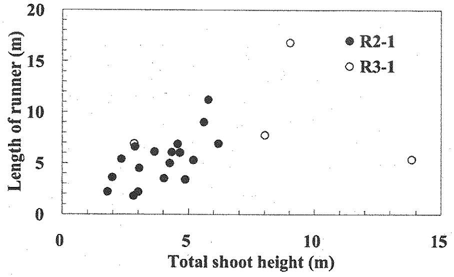


Fig. 5 Relationship between the total shoot height in a colony and the runner length of *P. japonica*. For the definition of R2-1 and R3-1, see Fig. 2.

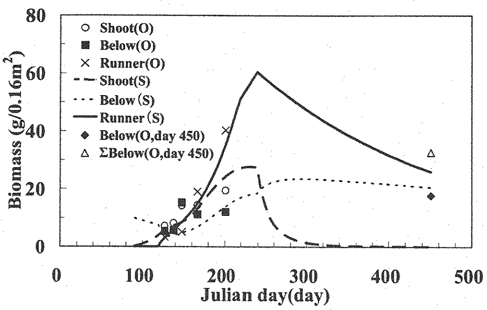


Fig. 6 Seasonal changes of shoot, belowground organ, and runner in *P. japonica*. Symbols represent the observed data (O). Lines are the simulated values (S). Σbelow denotes the cumulative value of belowground biomass in parent colony and colonies on the runner.

much, this finding indicates that the growth dynamic analysis has the potential to analyze the possibility of plant removal. The average strength of runners was 76.3±34.0 N, larger than the force necessary for removal, and the root biomass corresponding to the force for breaking runners was 3.16±1.40 g, much larger than that necessary for colony removal. Therefore, the removal of colonies is thought to occur earlier than the process of breaking the runner.

To compare the removal process with the picking up of the gravel around the plant, the removal force of C2-1 or C3-1, 20 N, which was smaller than the average removal force, was taken as a reference. In such a case, the average velocity of the stream can be assumed to be about 4.5 m/s (C_d = 0.5 from the experiment). On the other hand, the critical friction velocity and average velocity were calculated as 0.4 m/s and 2.8 m/s, respectively, even when the maximum diameter gravel, *d*, was 20 cm. This indicates that the removal process of the plants occurs later than the incipient motion of the gravel bed material, and that we must also evaluate the effect of drag forces that reduce the shear friction around the plant.

Fig. 10 depicts the long-term effects of *P. japonica* growth on gravel movement. Here we show A_{cri}/A_{con} , where A_{cri} expresses the area at which the friction velocity becomes lower than the critical friction velocity of medium size gravel (d_{50}), 0.01 m diameter gravel, by the effect of *P. japonica* growth, and A_{con} is the control area. This corresponds to the simulation in Fig. 7(c) and (d). The area in which sediment movement was affected was limited during the three years after colonization. The vegetation area could be enlarged as shown in the growth simulation (Fig. 7), but the plant density was very low. Thus, the effect of plants on gravel movement was less than 10% (A_{cri}/A_{con} = 0.10, line-A), quite limited for the three year period. On the other hand, densely populated stands were formed in the enlarged area after 4-5 years. If we defined the width that exceeds the threshold at A_{cri}/A_{con} = 0.25 (line-B) and A_{cri}/A_{con} = 0.50 (line-C) as W_{25} and W_{50}, respectively, the widths became 30 grids (12 m), and 10 grids (4 m), respectively, at year 4. The widths, W_{25} and W_{50}, increased exponentially in year 5 to 80 grids (32 m) and 60 grids (24 m), respectively.

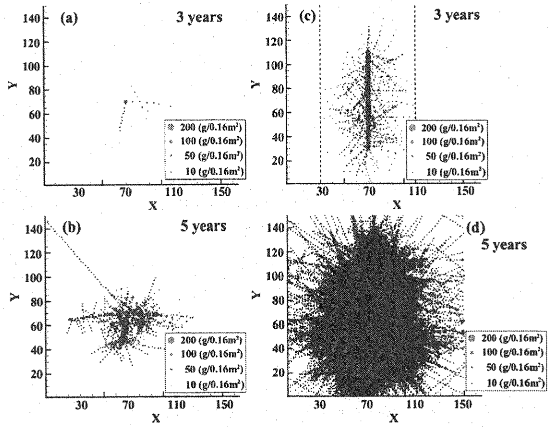


Fig. 7 Long-term aboveground dynamics of *P. japonica*, where *x*, *y* denotes the grid number and the grid distance is 0.4 m. Initial belowground biomass was set at 10 g/0.16 m^2 for one point in each case. Initial colonization was set as a point source at (*x*, *y*) = (70, 70) for (a) and (b), and as a lined source at *x* = 70, *y* = 30 - 110, (with 2 grids spacing) for (c) and (d). (a) 3 years (point source), (b) 5 years (point source), (c) 3 years (lined source), (d) 5 years (lined source).

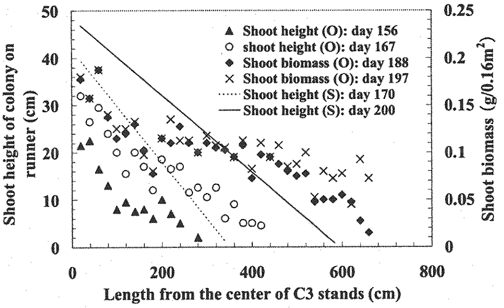


Fig. 8 Shoot height distribution along the runner from the center of the initial growth colony.

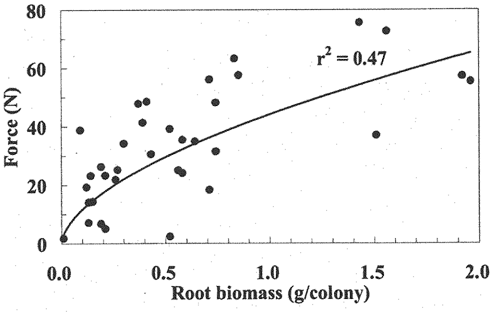


Fig. 9 Relationship between the root biomass and the removal force of *P. japonica* colony.

Further simulations were conducted to analyze the initial colonization effect on the area, as shown in Fig.11. W_{50} was affected by the initial colonization spacing. If the initial spacing was large (spacing = 1.2 m), W_{50} was rather small compared with cases with smaller spacing. Even then, W_{50} approached a similar value at year 5. Thus, 4-5 years after colonization

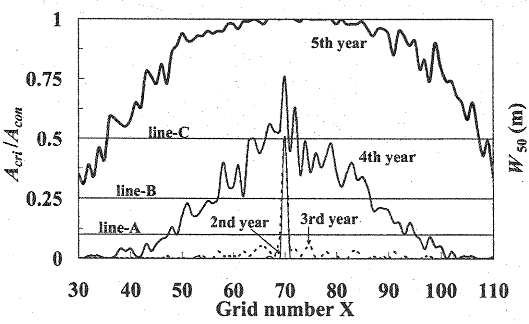


Fig. 10 Rate of the area at which the friction velocity falls below the critical friction velocity of 0.01 m diameter gravel due to the effects of *P. japonica* growth. Initial colonization was set at lined source (corresponds to Fig. 7(c) and (d)).

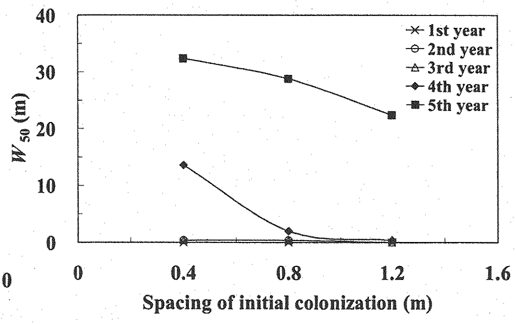


Fig. 11 Long-term effect of the initial colonization spacing of *P. japonica* on W_{50}.

has a very important meaning for *P. japonica*. If the flood interval at the *P. japonica* habitat is larger than 3 years, it becomes very difficult to restore the place to a gravel bed. This is a very important condition for the rehabilitation of a gravel-bed river. This interval is thought to change when a highly productive species is grown in the gravel bed of a river. In view of this matter, we must concentrate on the species differences and evaluate more general data concerning flood intervals necessary to maintain the gravel bed of a river in future observations and simulations.

CONCLUSION

To understand clearly the necessary flood intervals, the fundamental growth characteristics of *Phragmites japonica* grown on a gravel-bed river bar were investigated in the midstream of the Arakawa River, and the change of the critical friction velocity due to the plants was evaluated by a growth dynamics model of *P. japonica*. The length of runners was found to be closely related to the cumulative shoot height of the parent colony of the runner. Even a newly formed colony has enough strength to withstand a velocity higher than that necessary for the initiation of gravel movement. This indicates that the lateral distribution and seasonal development of a colony are very important factors in evaluating the colony's effects on flow resistance. By calculating the lateral biomass distribution, the shear stress was determined in accordance with the drag force by the plant. The simulation demonstrates that the friction velocity becomes much lower than the critical friction velocity of the bed material after 4-5 years of colonization. If the flood interval at the *P. japonica* habitat is longer than three years, it becomes very difficult to return the place to a gravel bed. This is a very important condition for the rehabilitation of a gravel-bed river. This interval is thought to change with other highly productive species in a gravel-bed in a river. Further research is needed in this respect to clarify the interaction between plant growth and gravel movement.

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