EurAsian Journal of BioSciences
Eurasia J Biosci 13, 1221-1224 (2019)

Sprinkler speed influence on soil substrate erosion

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Abstract

Considered work designed sprinkler with rotating wings in the conditions of growing seedlings in greenhouses, which eliminated the formation of erosion of the topsoil. The trajectory of the droplet flight during watering depending on the angular velocity of the wings of the sprinkler system is investigated. The relationship between the rotation frequency of the sprinkler, the angle of incidence and the kinetic energy of the droplets causing the destruction of the soil substrate of cassette seedlings is determined. Determined the rate of aretirement for soil substrate. In conclusion, recommendations are given to reduce the negative impact of drops on the soil substrate.

Keywords: irrigation, seedlings, irrigation radius, soil erosion

Olgarenko GV, Ryazantsev AI, Kuznetsov AV, Umaev DM, Beznosyuk RV, Kostenko My (2019) Sprinkler speed influence on soil substrate erosion. Eurasia J Biosci 13: 1221-1224.

INTRODUCTION

Vegetable farming in protected ground involves the cultivation of seedlings. With the cassette method, each plant is grown in a separate cell with rigid waterproof side walls and a drainage hole in the bottom. The cultivation of seedlings in cassettes reduces the energy costs for soil heating, provides the reduction of required area for seedling cultivation (Rembalovich et al. 2018, Ryazantsev and Antipov 2016, Ryazantsev et al. 2019). They use the flow system with pallets and sprinklers for seedling watering. The effectiveness of a sprinkler device during cassette seedling watering depends on irrigation radius and the angle of drop incidence from its end nozzles (**Fig. 1**).

The rotation of sprinkler wings is provided by the jet streams of sectoral deflector nozzles, located on the wings closer to the rotation center. Circular action nozzles are installed on the end parts of the sprinkler wings to irrigate the peripheral zone.

MATERIALS AND METHODS

The angle of droplet fall determines the erosion of the fertile layer. The sprinkler operation modes will determine the initial speed of drop flight, and accordingly the drop trajectory and their angle of incidence. Let's study the modes of the sprinklers that cause erosion processes (Melnichuk et al. 2018, Rembalovichet al. 2018, Ryazantsev et al. 2019).

Let's consider a sprinkler rotating at a constant angular velocity. Let's select the moving coordinate system $X_1O_1Y_1$ on the extreme sprinkler nozzle, and place the stationary XOY coordinate system on the horizontal platform where the sprinkler is located. The initial velocity of a drop flying out of a circular deflector nozzle is determined by the jet speed. The drop is affected by gravity, centrifugal force and air resistance force, which is proportional to the square of the velocity.

Let's make the differential equation of drop flight

$$\begin{cases} m\dfrac{d^2x}{dt^2} = F_{цб} - F^{x}_{сопр} \\ m\dfrac{d^2x}{dt^2} = -G + F^{y}_{сопр} \end{cases} \quad (1)$$

where m - drop weight, kg;

$F_{цб}$ – centrifugal force ($F_{цб} = m * \omega^2 * R$), H;

ω – sprinkler angular velocity, rad/s;

R – installation radius of the circular deflector nozzle, m;

$F_{сопр}$ - resistance to flying airborne droplets ($F_{сопр} = k * V^2$), H;

V – drop flight speed, m/s;

k – air resistance coefficient, H/($м/с^2$);

G – drop weight (G = m*g), H;

g – gravitational acceleration, $м/с^2$.

The values of forces are presented in equation (1)

$$\begin{cases} m\dfrac{d^2x}{dt^2} = m\omega^2 * R - kV_x^2 \\ m\dfrac{d^2y}{dt^2} = -mg + kV_y^2 \end{cases} \quad (2)$$

The projections of speed can be determined from the following expressions $V_x = V\cos(\alpha)$; $V_y = V\sin(\alpha)$.

Received: March 2019
Accepted: August 2019
Printed: September 2019

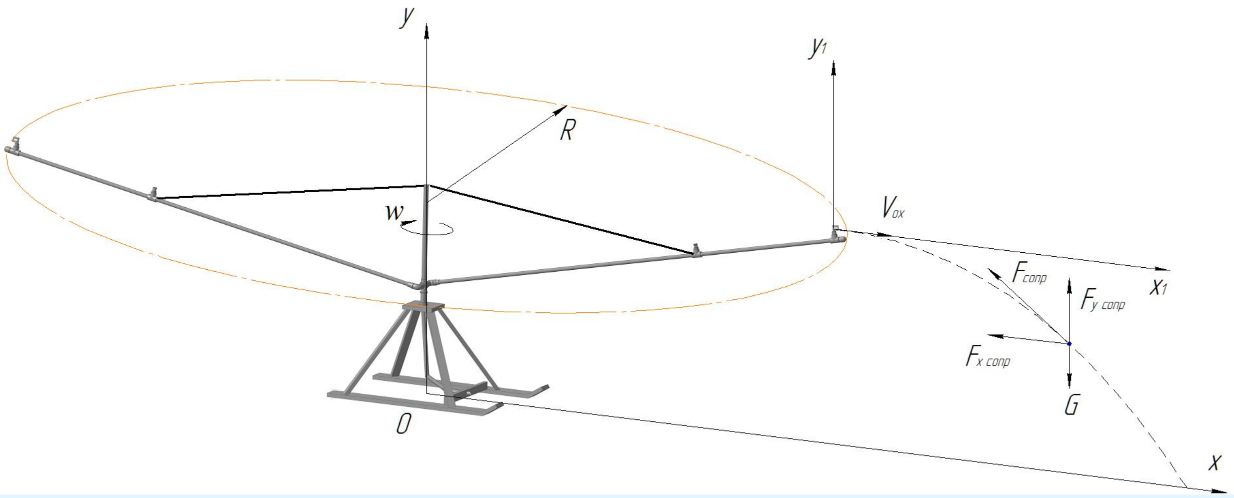

Fig. 1. Scheme sprinkler to determine the trajectory of the drops

Let's transform the equations (2) and separate the variables:

$$\begin{cases} m\dfrac{dV_x}{dt} = m\omega^2 * R - kV_x^2 \\ m\dfrac{dV_y}{dt} = -mg + kV_y^2 \end{cases} \quad (3)$$

$$\begin{cases} \dfrac{dV_x}{\omega^2 * R - \dfrac{k}{m}V_x^2} = dt \\ \dfrac{dV_y}{-g + \dfrac{k}{m}V_y^2} = dt \end{cases} \quad (4)$$

Let's introduce the notations $a^2 = \frac{m*\omega^2*R}{k}$; $b^2 = \frac{gm}{k}$ to simplify the transformations, then the equations (4) will be the following, let's integrate them:

$$\begin{cases} \displaystyle\int_{V_{ox}}^{V_x} \frac{dV_x}{V_x^2 - a^2} = -\frac{k}{m}\int_o^t dt \\ \displaystyle\int_0^{V_y} \frac{dV_y}{V_y^2 - b^2} = -\frac{k}{m}\int_o^t dt \end{cases} \quad (5)$$

After integration, we get the following:

$$\begin{cases} \dfrac{1}{2a} ln\left|\dfrac{V_x - a}{V_x + a}\right| \Bigg|_{V_{ox}}^{V_x} = -\dfrac{m}{k} * t \Bigg|_o^t \\ \dfrac{1}{2b} ln\left|\dfrac{V_y - b}{V_y + b}\right| \Bigg|_0^{V_y} = -\dfrac{m}{k} * t \Bigg|_o^t \end{cases} \quad (6)$$

Let's substitute the limits of integration and perform the calculations:

$$\begin{cases} \dfrac{1}{2a}\left(ln\left|\dfrac{V_x - a}{V_x + a}\right| - ln\left|\dfrac{V_{ox} - a}{V_{ox} + a}\right|\right) = -\dfrac{m}{k} * t \\ \dfrac{1}{2b}\left(ln\left|\dfrac{V_y - b}{V_y + b}\right| - ln\left|\dfrac{-b}{+b}\right|\right) = -\dfrac{m}{k} * t \end{cases} \quad (7)$$

Since the integration of system (7) equations is significantly different, let's consider each differential equation separately.

Considering that the value of the constant coefficient is equal to $a=\sqrt{\frac{m*\omega^2*R}{k}}$ and $b=\sqrt{\frac{m*g}{k}}$ let's transform the difference of logarithms and divide the variables in the equation on the ordinate axis:

$$\begin{cases} ln\left|\dfrac{(V_x - a)(V_{ox} + a)}{(V_x + a)(V_{ox} - a)}\right| = -\dfrac{2am}{k}t \\ ln\left|\dfrac{(V_y - b)(+b)}{(V_y + b)(-b)}\right| = -\dfrac{2bm}{k}t \end{cases} \quad (8)$$

Let's potentiate the equations (8):

$$\begin{cases} \dfrac{(V_x - a)(V_{ox} + a)}{(V_x + a)(V_{ox} - a)} = e^{-\frac{2am}{k}t} \\ \dfrac{(V_y - b)}{(V_y + b)} = e^{-\frac{2bm}{k}t} \end{cases} \quad (9)$$

Let's transfer the constant factor to the right side of the equation:

$$\begin{cases} \dfrac{V_x - a}{V_x + a} = \dfrac{V_{ox} - a}{V_{ox} + a} * e^{-\frac{2am}{k}t} \\ -\dfrac{b - V_y}{b + V_y} = e^{-\frac{2bm}{k}t} \end{cases} \quad (10)$$

Let's transform the equation (10) into the following form:

$$\begin{cases} V_x = a\,\dfrac{V_{ox}\left(e^{-\frac{2am}{k}t} + 1\right) - a\left(e^{-\frac{2am}{k}t} - 1\right)}{-V_{ox}\left(e^{-\frac{2am}{k}t} - 1\right) + a\left(e^{-\frac{2am}{k}t} + 1\right)} \\ V_y = -b\,\dfrac{1 - e^{-\frac{2bm}{k}t}}{1 + e^{-\frac{2bm}{k}t}} \end{cases} \quad (11)$$

Taking into account that $\frac{dx}{dt} = V_x$, $\frac{dy}{dt} = V_{xy}$ let's divide by it the right side of the expression dt and integrate:

$$\begin{cases} \displaystyle\int_{x_0}^{x} dx = a\int_0^t \frac{V_{ox}\left(e^{-\frac{2am}{k}t} + 1\right) - a\left(e^{-\frac{2am}{k}t} - 1\right)}{-V_{ox}\left(e^{-\frac{2am}{k}t} - 1\right) + a\left(e^{-\frac{2am}{k}t} + 1\right)}dt \\ \displaystyle\int_{y_0}^{y} dy = -b\int_0^t \frac{1 - e^{-\frac{2bm}{k}t}}{1 + e^{-\frac{2bm}{k}t}}dt \end{cases} \quad (12)$$

After integration we obtain the following:

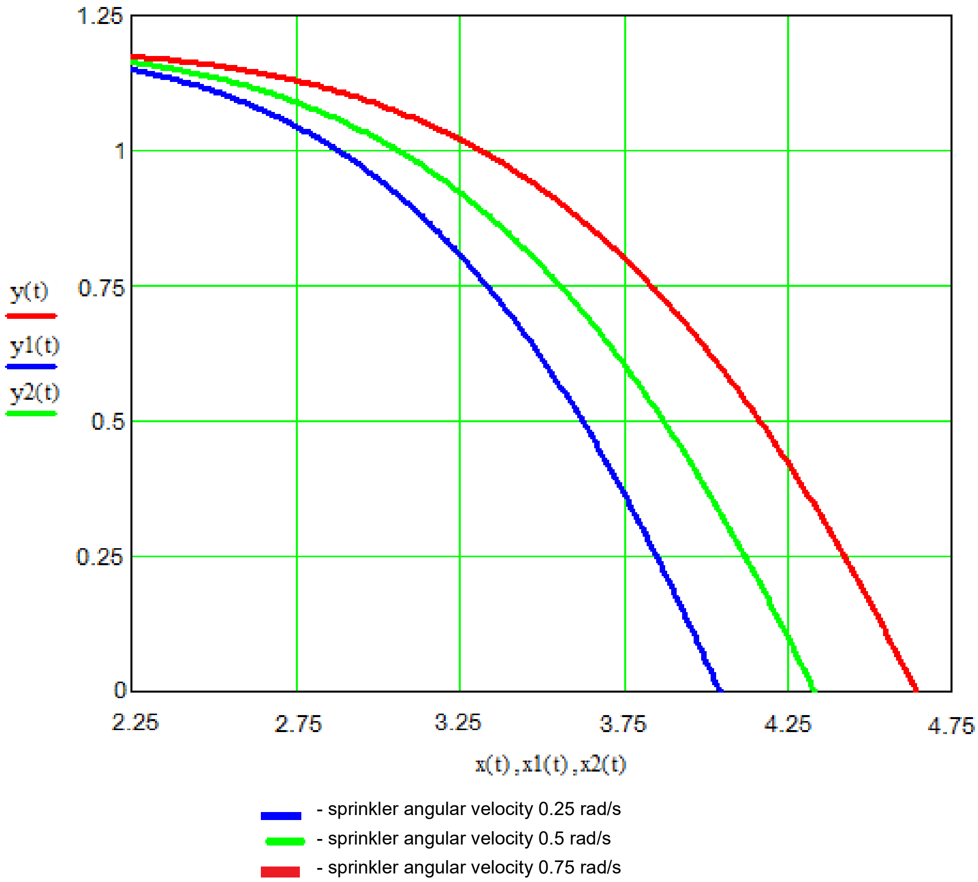

Fig. 2. The trajectory of droplets during sprinkler wing rotation with different angular velocity

$$\begin{cases} x - x_0 = a \dfrac{ln\left(\dfrac{b - V_{0x} + b * e^{-\frac{2amt}{k}} + V_{0x} * e^{-\frac{2amt}{k}}}{b + V_{0x}}\right) * \left(k * b^2 + k * {V_{0x}}^2\right)}{b^3 * m + b * m * V_{0x}^2} - \\ \quad - \dfrac{t * (b - V_{0x})}{b + V_{0x}} + \dfrac{2 * b * m * t * (k * b^2 + k * {V_{0x}}^2)}{k * (b^3 * m + b * m * V_{0x}^2)} \\ y - y_0 = -b * t - \dfrac{k * ln(e^{-\frac{2bmt}{k}} + 1)}{m} \end{cases} \quad (13)$$

Finally, we have the following:

$$\begin{cases} x = x_0 + a \dfrac{ln\left(\dfrac{b - V_{0x} + b * e^{-\frac{2amt}{k}} + V_{0x} * e^{-\frac{2amt}{k}}}{b + V_{0x}}\right) * \left(k * b^2 + k * {V_{0x}}^2\right)}{b^3 * m + b * m * V_{0x}^2} - \\ \quad - \dfrac{t * (b - V_{0x})}{b + V_{0x}} + \dfrac{2 * b * m * t * (k * b^2 + k * {V_{0x}}^2)}{k * (b^3 * m + b * m * V_{0x}^2)} \\ y = y_0 - b * t - \dfrac{k * ln(e^{-\frac{2bmt}{k}} + 1)}{m} \end{cases} \quad (14)$$

RESULTS AND DISCUSSION

Using the Mathcad program and the required parameter values, let's study the droplet flight trajectory.

Fig. 2 shows that the angular velocity of the sprinkler wings determines the angle of droplet incidence. Also, the angular velocity affects the droplet distribution distance. Falling drops have kinetic energy, causing the destruction of the cassette seedling soil substrate. When the substrate is sufficiently wetted, a drop fall forms a spray as the result of impact, representing the mixture of water and destroyed soil aggregates which scatter to the sides (DePloy 1984, Rembalovich et al. 2018, Zaslavsky 1987). Moreover, the angle of droplet flight affects the direction of spray flight; the sharper the angle, the greater the amount of water and destroyed soil aggregate mixture moves into the adjacent cells of the cassette. With falling drop range increase, their speed will increase, and soil erosion will occur at certain drop sizes. To reduce the effect of droplets on cassette seedlings, one should limit the rotation frequency of the sprinkler wings and droplet size. Rational values of the angular velocity of sprinkler wings with the length of 2.25 m are determined on the basis of cell size and soil substrate properties of the cassette seedlings and make 0.52 rad/s.

Water permeability is the most important characteristic of a soil substrate determining erosion. The total consumption of the sprinkler Q is determined by the following expression:

$$Q = \rho \times S \quad (15)$$

where ρ is the average rain intensity during the irrigation of cassette seedlings, mm / min;

S - the area irrigated by a sprinkler on the position, m^2.

The following volume of water gets to a cassette cell in one minute at a given rain intensity:

$$W = 10 * \rho_c * S \quad (16)$$

where W- the minute volume of water entering the cassette cell, cm^3/min;

ρ_c- the average rain intensity, mm/min;

S – cassette cell area, cm^2.

The second mass of the irrigation solution falling into the cassette cell will be the following:

$$m_c = \frac{10 * \rho_c * S * \gamma}{60} \quad (17)$$

where m$_c$ – second supply of water in the cassette cell, g/s;

γ – the irrigation solution density, g/cm^3.

Obliquely falling droplets form the micro flows that contribute to erosion:

$$\Delta m = m_c \sin \alpha \quad (18)$$

Δm – the micro flows in the cassette cell contributing to soil substrate erosion, g/s;

α – drop incidence angle, grad.

The work performed by erosion micro-flows in a cassette seedling cell will be the following:

$$A = 10^{-3} * \Delta m * V * L \quad (19)$$

where *A* – the work of raindrops in a cassette cell, J;

V – the average velocity of droplets, m/s;

L– cassette cell size, m.

For soil substrate of cassette seedlings, the erosion index can be written in the following form:

$$E = \frac{P}{A} \quad (20)$$

where E is the erosion index of the substrate in the cassette cell, g/J;

P is the soil substrate mass washed out of the cell, g.

The use of artificial irrigation with a sprinkler can cause soil erosion (Tornz 1984, Zaslavsky 1987). J. Moersons and De Ploy consider erosion as the displacement of soil particles after the impact of raindrops — drop creep (Moeyersons 1976). Similar wording was suggested by Timofeev, which takes into account the impact on the soil substrate, along with raindrops and hailstones (Timofeev 1978). Scheidegger defines drop-rain soil erosion as the direct separation of soil particles during the impact of raindrops and their displacement for some distance (Scheidegger 1964). Soil erosion due to droplet impact during the irrigation of cassette seedlings is especially dangerous with small volumes of soil substrate in cells.

CONCLUSIONS

The angular velocity of the sprinkler wings determines the angle of droplet incidence. Falling drops have kinetic energy that can cause the destruction of cassette seedling soil substrate. With falling drop range increase, their speed will be also increased, and soil erosion will occur at certain drop sizes. Rational values of the angular velocity of 2.25 m sprinkler wings are determined on the basis of the cell size and the properties of the soil substrate of the cassette seedlings and make 0.52 rad/s. In order to reduce the effect of droplets on cassette seedlings, limit the sprinkler wing rotation frequency and droplet size.

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