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Laboratory investigation of *Fallopia x bohemica* fruits dispersal by watercourses

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Abstract Seed and fruit dispersal along watercourses favours the long-distance migration of invasive species, not only for aquatic or wetland species, but also for terrestrial wind-dispersed plants, like the japanese knotweed. The present paper aims at investigating the role of watercourses in the dispersal of the knotweed due to its frequent occurrence on riverbanks and production of fertile achenes (type of fruit of the japanese knotweed). This dispersal occurs along two steps after the fruits deposit on the water surface: floatation first and then sinking towards the bottom of the watercourse. Regarding the first step, the effects of agitation of the water, temperature, surface tension and luminosity on the achenes floatability are experimentally studied. While no influence of luminosity is observed, an increase of temperature greatly decreases the floating time. Floating time also decreases as the contact between water and the fruit is enhanced (through submersion of achenes, agitation of the water or lower surface tension). Regarding the second step, the fall velocity of the fruits in water at rest is measured and appears to be independent of the seed history (floating time). 3D helical motions are systematically observed with constant tangential velocity with respect to the falling velocity. The trajectory of the fruits in a shear flow is then measured and the evolution of their velocity

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components along the sinking process is discussed. Finally, the contribution of both steps to the long-distance migration of the seeds is estimated.

Keywords Buoyancy · Settling velocity · Achene · Fruit hydrodynamics · Hydrochory · Helical motion · Shear flow

1 Introduction

Biological invasions are known to be an important issue in the loss of biodiversity. The japanese knotweed, also referred as *genus Fallopia* or *Reynoutria*, is one of the 100 most invasive species [7]. Recent studies showed that the sexual reproduction of the japanese knotweed highly contributes to its dispersion in Belgium [22], Czech Republic [10] and USA [8]. The japanese knotweed mainly settles on riverbanks in riparian zones where the hydrochory (*i.e.* its spreading by watercourses) is the main process of propagation [20] even though Varshney et al. [23] state that *multiple-winged seeds* (such as *Fallopia*) *exhibit complex aerial movements which assist their long distance propagation*. Rouifed et al. [18] confirmed that watercourses are an efficient way of dispersion for the japanese knotweed. Note that while rare events such as floods or zoochory are, even though improbable, very efficient for very long distance dispersal [13], the present paper focuses on the deterministic long-distance dispersal of japanese knotweed fruits by watercourses.

Hydrochory is mainly governed by the diaspores density, size and shape [3] and can be split in two main behaviours, depending on the diaspore density: buoyant diaspores that float on the surface and non-buoyant ones that sink. The buoyancy depends on the anatomical structure of the pericarp (the envelope of the fruit) and more particularly the presence of aeriferous tissue (conducting air) in the exocarp, the external layer of the pericarp [9,15,17]. Moreover, buoyancy is highly correlated with the shape of the diaspores [25]. Oppositely, even if the size of the achenes highly differs from one individual to another, it did not appear as a main factor in buoyancy studies by Hroudová et al. [9] and Coops and Van der Velde [4]. The dispersal of non-buoyant diaspores can be depicted by the well studied mechanisms governing mineral sediment transport in rivercourse [12]. The fundamental property characterizing the deposit of a non-buoyant seed is the ratio between its settling velocity and the mean stream velocity [3,24]. Regarding buoyant seeds, studies were dedicated to the influence of wind, obstacles and vegetation on their dispersal along the free-surface. The results show that diaspores follow the free-surface stream and that differentiation between species is not significant without wind [3].

Rouifed et al.[18] show that when detaching from the tree and falling in a watercourse, the dry fruits of the japanese knotweed float. While floating they absorb water, become waterlogged and finally sink. They thus exhibit both buoyant and non-buoyant behaviours one after the other. Both floating and non-floating hydrochory mechanisms thus have to be investigated to fully understand the japanese knotweed dispersal. A key parameter for the japanese knotweed fruit dispersal is the floating time after which the fruits are waterlogged enough to sink (*i.e.* with a density higher than unity). Furthermore, the floating time should be regarded in

respect to the watercourse flow rate. Indeed, if the floating time of a diaspore is higher than the ratio of the watercourse length by its bulk velocity, a non buoyant study is irrelevant [1]. On the other hand, as clearly stated by Varshney et al. [23]: *The falling dynamics of seeds are critical for understanding their dispersal properties*. Similarly the settling characteristics of seeds in water may strongly affect the dispersal characteristics and will thus be investigated herein.

The influence of environmental parameters on the vegetation growth has been widely studied [19], however their influence on the floating time and the settling velocity remains poorly documented. Indeed, the floating time is usually measured in controlled laboratory conditions for a unique temperature, under a defined luminosity and for one quality of water while these parameters vary along time and space in a given watercourse.

The aim of the present work is to better understand the influence of environmental parameters on the time and motion characteristics of the fruit as they reach a watercourse, *i.e.* as it floats and then as it sinks.

In a first section, we aim at evaluating the influence of the environmental parameters on the fruit's floating time: agitation of water, temperature, water quality and enlightenment. Then, the second section is dedicated to the measurement of settling velocity and the three-dimensional motion of the fruits in water at rest. Finally, the falling motion of fruits in a shear flow is investigated. In each of these three sections, the corresponding materials and method are first presented, followed by the results. The last section is dedicated to a general discussion and the conclusions of this work.

2 Floatability analysis

2.1 Achene sampling

The achenes considered herein were collected by the Laboratoire d'Écologie des Hydrosystèmes Naturels et Anthropisés (LEHNA) in december 2012 from *Fallopia x bohemica* stands growing in Bourgoin-Jallieu in the Département de l'Isère (France). They were randomly selected from several *Fallopia* shoots of the same stand to reduce variability and then pooled. The achenes were stored in dry conditions at 4°C until they were used for experiments. Preliminary tests showed that these sampling and storage methods do not affect the germination rates [18].

2.2 Experimental setup

The experimental setup for the floatability study is made of two 20x30x20cm pools sketched in Fig. 1. These pools are immersed in a large transparent tank of water. Some holes in the bottom of these pools guarantee the same temperature (measure with a thermocouple) and water quality between both pools and the tank. A long and thin pipe (8mm diameter) is fixed all along the bottom's perimeter of the pools and is linked to an air compressor (Fig. 1a). Small holes in this pipe allow

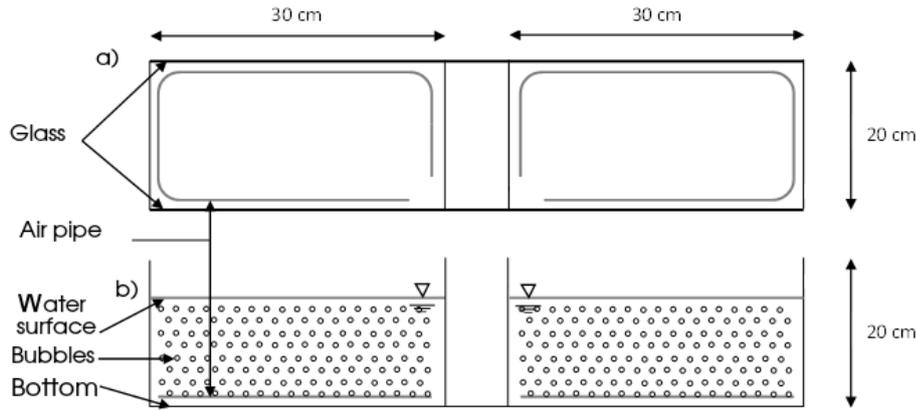


Fig. 1: Sketch of the experimental device for free surface studies - a) top view b) front view

air bubbles to escape and rise in the pools towards the free surface, thus agitating the volume of water in each pool as shown on Fig. 1b. The pipes are equipped with a valve allowing to adjust the air discharge and then to vary the agitation intensity. With such a device, air bubbles are periodically shed from each hole and generate a vertical motion towards the free surface as they rise. This agitation limits the concentration of the fruits in specific regions of the free surface where they would accumulate and interact with each other.

This whole set-up is placed either in a large hall with a glass-roof, *i.e.* receiving natural lighting during day time with a non-controlled temperature or in a closed room with artificial light and controlled ambient temperature. The water used in the experiments is either "clean" (degassed tap water, surface tension of 70 mN/m) or "highly polluted" by adding soap to decrease its surface tension (30 mN/m). Sridhar and Reddy [21] collected surface tension data from water from natural, industrial or domestic waters and reveal that in polluted natural watercourses the surface tension decreases from about 73 mN/m (for clear water at 20 °C) to about 50 mN/m.

Both front and rear side of the pools are made of glass in order to ensure an optimal optical access. A 640*480 pixels camera is placed in front of each pool to visualize the bottom of the pools. A mirror located behind the pools and slightly inclined allows to visualize the free surface with the same camera.

For each experiment, one hundred fruits are deposited on the free surface of each pool at $t=0$ and afterwards a picture is taken every five minutes. A semi-automated image analysis allows to count the number of floating fruits in each pool along the time.

Additionally, another set up consisting of a simple tank allows to study the floating time of immersed fruits (see Table 1). In this case, the fruits are placed under a net placed one centimeter below the water surface, as shown in Fig.2. In order to study the behaviour of the fruits under different environmental conditions 16 floatability experiments are run with the following varying parameters: agitation of water or immersed fruits, water temperature and surface tension (see columns

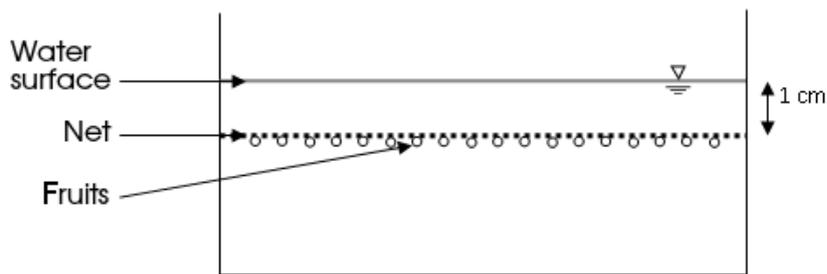


Fig. 2: Sketch of the specific experimental device used for studying the immersed fruits

2 to 4 in Table 1). Besides, to evaluate the influence of illumination, experiment 8b was run in the dark.

2.3 Results

For each configuration of Table 1, the ratio of floating fruits is plotted against time as in Fig.3 for experiment 1a. Note that apart from experiment 0 for which the fruits do not sink, the figures corresponding to all experiments exhibit the same trend: as they are deposited on the water surface ($t=0$) the fruits first float, then after a few hours, the first fruits start to sink, the sinking rate increases, reaches a maximum value and decreases. The few fruits remaining on the free-surface at the end of the experiment germinate on the free surface. Note that in Table 1 the subscripts a and b refer to the first and the second pool respectively. $t_{50\%}$ and $t_{75\%}$ are then defined as the times after which 50% and 75% of the fruits have sunk, respectively. Note that for an agitated flow, as the density of the fruit reaches 1, the fruit does not sink towards the bottom but rather remains in the water column and follows the water motion. In such case, a fruit is considered as sunk when it finally settles at the bottom of the pool.

All experimental conditions and corresponding results are summarized in Table 1. Following observations can be made:

- Experiment 0 reveals that in clean water at rest, the fruits do not sink. The sketch in Fig. 5a and the photograph in Fig. 6a reveal that as the fruit is deposited on the water surface, an air bubble is trapped between the water and the fruit which prevents from direct contact and thus from an efficient water absorption.
- Experiments 1,2 and 3 reveal that as clean water is agitated, the fruits end up sinking after an average of 40 hours. Moreover these experiments show a small, yet noticeable influence of the strength of agitation on the fruits' floating time: it decreases as the agitation intensity increases (see Fig. 4a).
- Experiments 1a, 2a and 3a, driven at the same agitation intensity but at different temperatures reveal that the floating time strongly decreases as the water temperature increases. It ranges from $t_{50\%} = 57h$ for a constant temperature

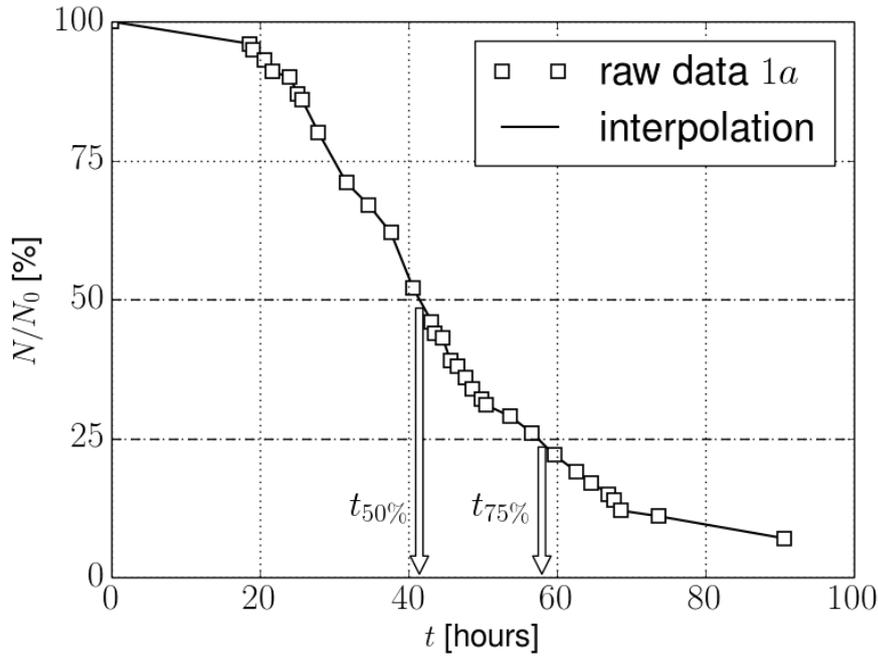


Fig. 3: Time evolution of the ratio of number of floating fruits N over initial number of fruits N_0 . Raw data (squares) is obtained from 1a experiment (see Table 1), linear interpolation (solid line) is used to extract the characteristic floating times $t_{50\%}$ and $t_{75\%}$ at which 50% and 75% of the initial number of fruits have sunk, respectively

Table 1: Conditions and results of the 17 buoyancy experiments. a and b refer to the first and the second pool respectively. * refers to the non controlled temperature experiments for which only min-max values of the water temperature are given.

Name	Agitation	$T_{water} (^{\circ}C)$	Surface tension (mN/m)	$t_{50\%}$	$t_{75\%}$
0	None	23-28*	70	-	-
1a	Strong	23-28*	70	41h	57h
1b	Weak	23-28*	70	49h	62h
2a	Strong	20	70	57h	80h
2b	Mean	20	70	66h	80h
3a	Strong	27	70	29h	36h
3b	Mean	27	70	31h	40h
4	None	20	30	42h	59h
5	None	27	30	21h	24h
6a	Immersed	20	70	28h	38h
6b	Immersed	27	70	25h	31h
7a	Immersed	20	30	22h	29h
7b	Immersed	27	30	15h	17h
8a	Strong	22-26*	70	51h	65h
8b (in the dark)	Strong	22-26*	70	51h	65h

of 20°C to $t_{50\%} = 29h$ for a temperature of 27°C (the same tendency is obtained comparing experiments 2b and 3b, 4 and 5, see Fig. 4b).

- Experiments 4 and 5 are driven without agitation in "polluted" water to analyse the effect of surface tension on the fruits buoyancy. First observation is that the fruits actually sink while this was not the case for "clean" water without agitation. Moreover, the average sinking time $t_{50\%}$ appears to be lower for the "polluted" water at rest than for the agitated "clean" water (see Fig. 4c).
- Experiments 6 and 7 are driven with fruits maintained below the water surface, performed respectively with "clean" and "polluted" water, showing that the immersion reduces the floating time.

The following conclusions can be made: by comparing experiments 0, 2a, 4, and 6a, it is concluded that the contact between the fruits and the water (agitation or immersion) strongly influences the fruits' floating time (twice shorter for the immersed fruits). The effect of the agitation is thus to limit or cancel the influence of the air trapped below the fruit in water at rest (see Fig. 6a). Nevertheless even with a strongly agitated flow, water contact remains limited to the bottom half of the fruit surface. Also, as the surface tension decreases, the contact between the fruits and the water increases. As a fruit is deposited on the surface of "polluted" water, the center part is situated below the surface, two wings lie on the water whereas the third one is immersed, facing downwards as it is shown in Fig. 5. The pictures in Fig. 6b confirm this behaviour which could explain the increased ability of the fruits to absorb water in a polluted medium. With the immersed fruits, this contact surface between fruit and water is maximized, increasing the water logging and thus reducing the floating time with regards to all other configurations. Furthermore, the immersed fruits sink earlier in polluted water than in clean water, indicating that pollution has an influence on water absorption mechanisms of the fruit. Finally, in all configurations (except in clean water at rest), the floating time decreases as the temperature increases. Temperature is an important factor inducing seed germination: under wet conditions, increased temperature favors and accelerates induction of seed germinations [16,2]. The changes occurring during germination (embryo development, use of reserves, alteration of seed coat..) are probably involved in the change of buoyancy observed for the seeds of *Fallopia*. This may explain why the temperature, which controls these processes, may greatly influence the changes of buoyancy observed.

It should be additionally noted that the influence of the three parameters are cumulative. To conclude this floatability analysis, the floating time reduces as:

- the floating fruit/water contact increases
- the temperature of the water increases
- the water is polluted

The experimental range of these parameters seems representative of natural watercourse parameters. "Weak agitation" corresponds to limited secondary currents and turbulent energy (just strong enough to evacuate air bubbles) while "strong agitation" corresponds to the presence of, for instance, helical secondary cells in river bends, to boils, emerging boulders, or soaking branches in rivers; surface tension ranges from pure to polluted water in rivers, temperatures from 20°C to 28°C correspond to seasonal variations of typical river temperatures. These variations of quantitative parameters lead to floating times in the range of 17 to

60 hours. This floating time can be considered as $O(10 \text{ h})$ *i.e.* of the order of some tens of hours.

3 Free fall in water at rest

3.1 Experimental setup

The fruits' settling velocity measurements are performed in a 20x18x70cm transparent tank filled with clean water. A 1920*1080 pixels camera and a plane mirror are used to record the three-dimensional fruits' motion. A light source is located behind the tank and the shadow of the fruit is recorded by the camera. Thanks to the plane mirror, the pathline of the fruits in two orthogonal planes is recorded, which permits to reconstruct the 3D trajectory. This technique, known as 3D Particle Tracking Velocimetry (PTV) is presented in Varshney et al. [23]. Because of the small size of the fruits compared to the field view of the camera, the angular position of the fruits during the fall cannot be obtained. To obtain fruits with a density larger than unity, a large amount of dry fruits is first deposited at the surface of the pools (see Sect. 2.2) filled with polluted water (in order to reduce their floating time). When a fruit sinks, its floating time is recorded, it is removed with care from the pool and deposited in a tank filled with clean water, just below the surface to avoid the influence of surface tension. It then sinks within the clean water tank. Through image analysis of the recorded pictures, the three-dimensional pathline of the fruit against the depth is obtained and the mean settling velocity is computed. This allows to investigate the influence of the floating time of a fruit on its mean settling velocity.

3.2 Results

Settling velocity The mean fruits settling velocity is plotted against the floating time of the fruit in Fig. 7 for 42 fruits. For a given floating time, these results show a great variability of velocity from a fruit to another, mostly due to specific geometry parameters. Averaged velocities (black squares) are thus also included in the figure. No clear influence of floating time on the settling velocity can be observed. Hence the influence of the floating time will be discarded in further analyses of sinking fruits. Averaging all data from Fig. 7, the ensemble averaged vertical settling velocity $\langle v_y \rangle$ finally equals 0.41 cm/s with a standard deviation of 0.25 cm/s where $\langle \cdot \rangle$ stands for the ensemble averaging of the mean velocity values. By comparison with literature, non buoyant fruits' settling velocity ranges from 0.9 to 2.7 cm/s [3]. The reasons for which the present fruits have a lower settling velocity is likely to be related to their lower relative density which may be closer to 1.

3D motion Varshney et al. [23] review the four well-known type of bodies falling motion including "autogyration", "rolling gyration", "floating" and "undulation" motion. In the present case, when sinking towards the bottom in water at rest, all fruits exhibit a coupled autogyration/rolling gyration. Such a coupled motion has already been observed on tulip seeds falling in air by McCutchen [11] and is similar

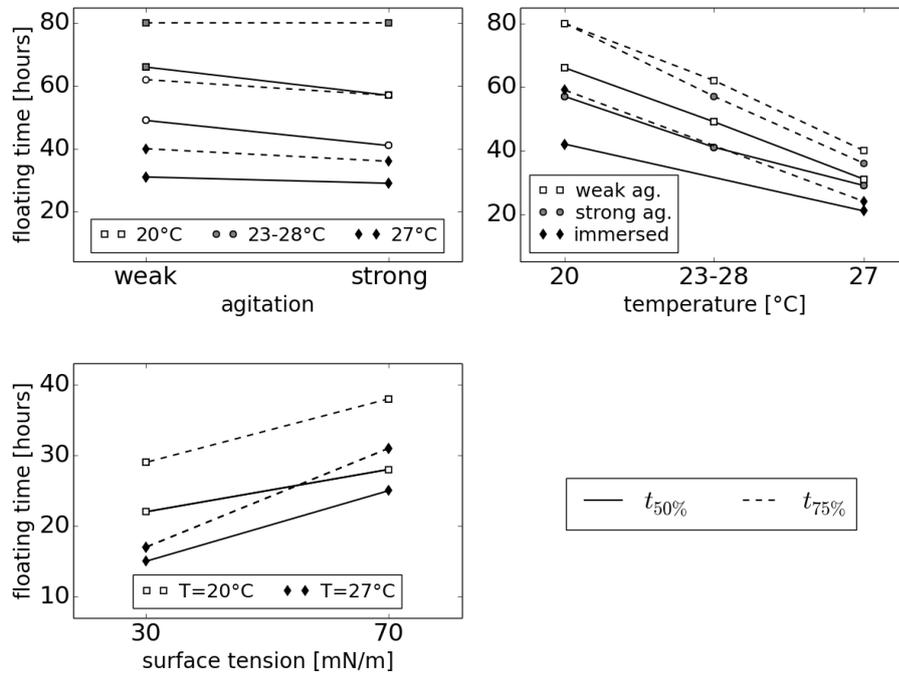


Fig. 4: Influence of (a) agitation, (b) temperature and (c) surface tension on fruits floating time - $t_{50\%}$ (respectively $t_{75\%}$) denotes the time after which 50% (respectively 75%) of the initially deposited fruits have sunk

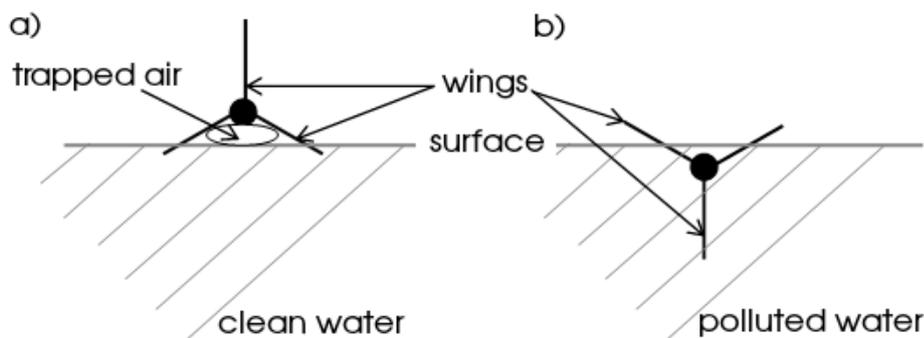


Fig. 5: Schemes of fruit position when falling or deposited on water surface with a high tension surface (clean water, a) and low tension surface (polluted water, b)



(a) Clean water at rest (no agitation)



(b) Polluted water

Fig. 6: Pictures of buoyant fruits deposited on clean water (a) and on polluted water (b)

to the Fig. 2 presented in [23]. From now on this motion will be referred as "helical" for simplicity. In our experiments, a great variability is observed on the helix radius ($[1-15\text{ cm}]$, see Fig. 8) and on the vertical mean velocity v_y ($[\pm 0.5\text{ cm/s}]$) without any correlation between them. A helical pathline with very large radius is presented in Fig. 8a whereas a helical pathline with small radius is presented in Fig. 8b. The smallest radius recorded is 5 mm and the largest one is 70 mm .

Oppositely, limited variability is observed on the ratio of mean tangential velocity over vertical velocity v_{\perp}/v_y . The ensemble average value of this ratio is $\langle v_{\perp}/v_y \rangle = 0.25$ and the corresponding standard deviation is about 0.1.

The following conclusions can be raised for this free-fall section: (i) the settling velocity of the fruits does not depend on its floating time ; (ii) the mean settling velocity is low compared to the literature of non buoyant fruits ; (iii) the fruits exhibit a helical motion with a high variability of vertical velocity and radius ; (iv) the mean tangential velocity of the helical motion is about 25% of the mean vertical velocity.

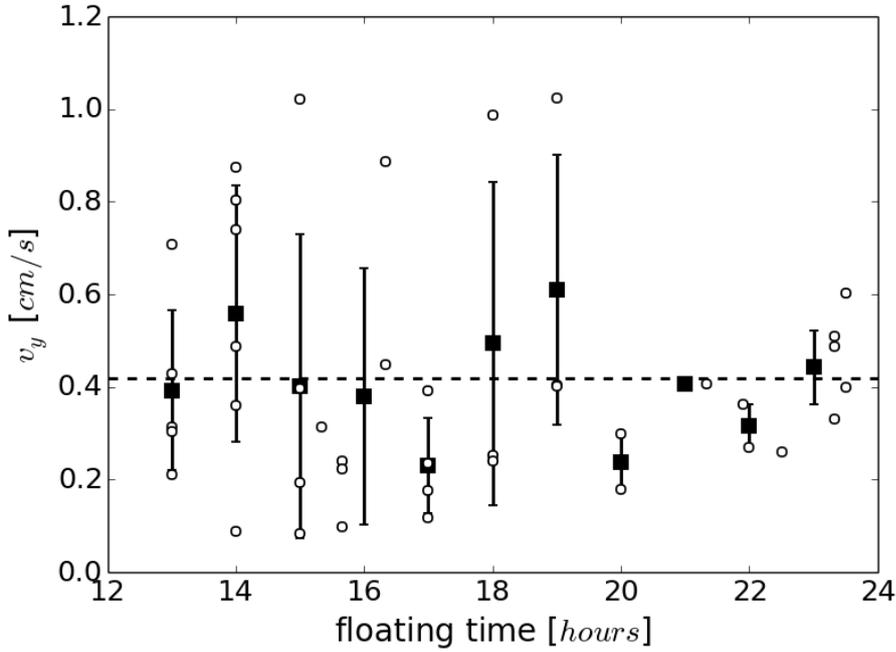


Fig. 7: Mean settling velocity (v_y : \circ) obtained for 42 free fall experiments as a function of the floating time. Average ensemble value ($\langle v_y \rangle$) and standard deviation σ are computed for each hour interval (\blacksquare and bars) and for the whole set of fruit (dash line)

4 Free fall in a shear flow

The present section aims at investigating the characteristics of the trajectory and velocity of the fruit as it settles within a steady shear flow, representative of a river flow.

4.1 Experimental setup

The experiments are performed in a $b = 25\text{cm}$ wide and 8 m long horizontal flume with a steady subcritical flow and a streamwise bulk velocity $U = 3\text{cm/s}$, a water depth $h = 22\text{cm}$, a Froude number $Fr = 0.006$ and Reynolds number $Re = \frac{4Ubh}{(b+2h)\nu} = 9600$. The geometrical aspect ratio of the flow section b/h is about equal to 1, which tends to generate secondary currents with a downward velocity in the center section of typical magnitude equal to a few percent of U , according to Nezu and Nakagawa [14]. x refers to the streamwise axis and y to the vertical axis. u refers to the velocity of the flow and v to the fruit velocity.

About one hour after it sinks within the polluted water pool used in Sect. 2, each tested fruit is deposited slightly below the surface at the upstream section of the test region ($x = 0$). The one hour delay ensures a density slightly larger than

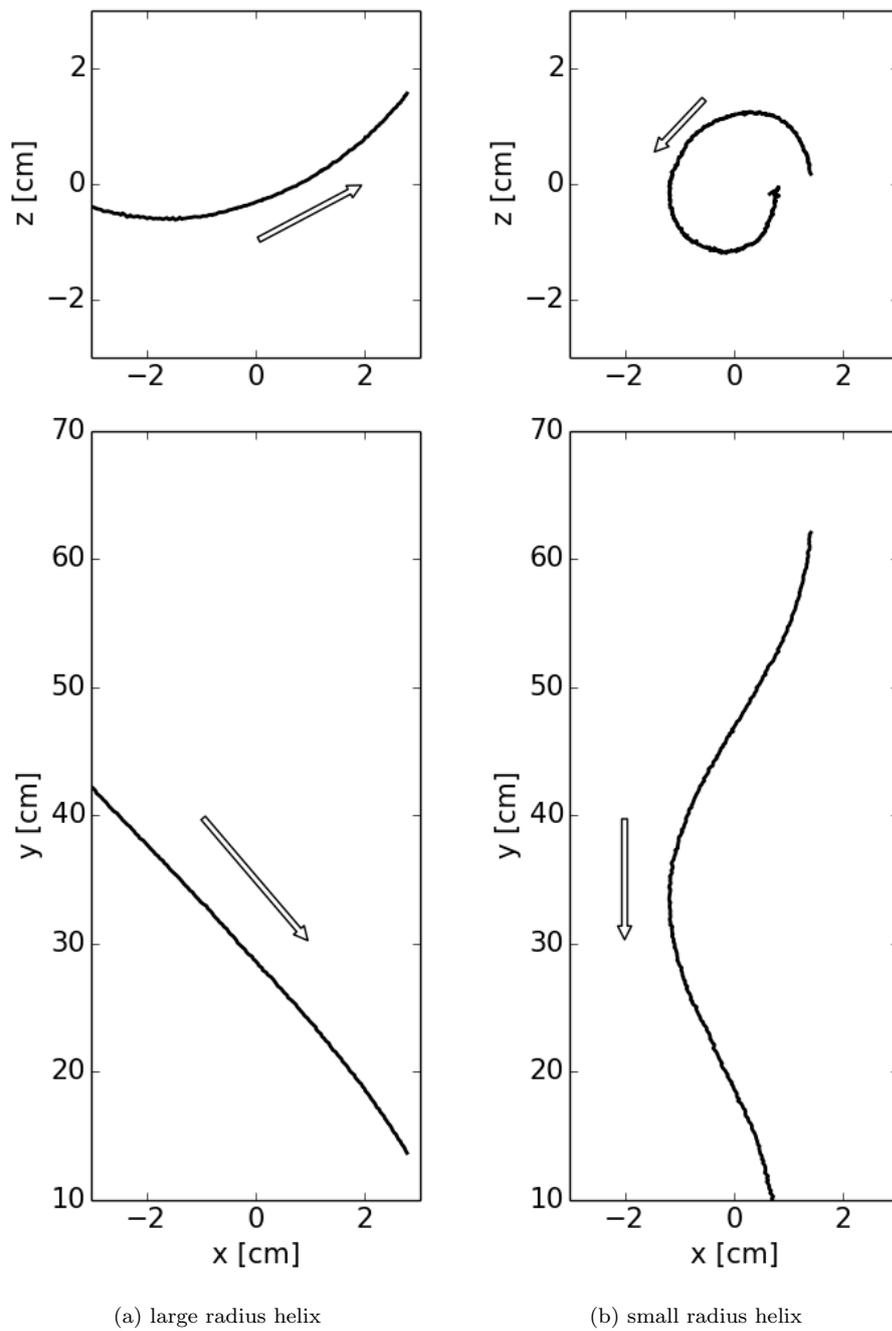


Fig. 8: Top and front view of the 3D helical motion of two sinking fruits. For case a, only a short portion of the settling motion is recorded due to a helical radius much larger than the window recorded by the camera.

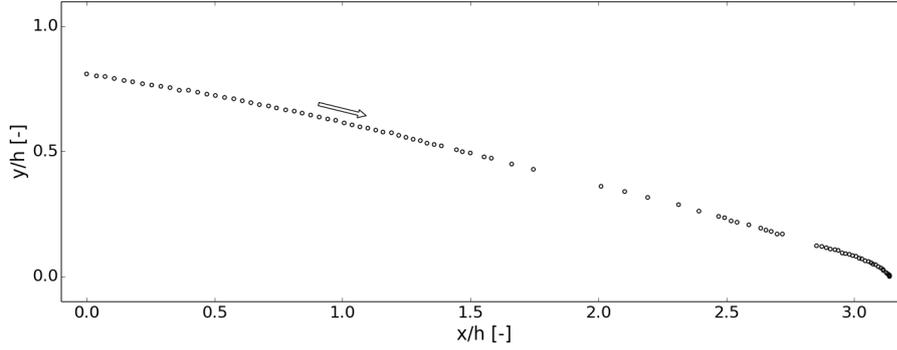


Fig. 9: Pathline of one fruit in established sheared flow ; long distance between consecutive locations corresponds to times at which the location of the fruit could not be recorded.

1 and thus that the fruit actually sinks in the sheared flow. The two-dimensional pathline of the fruit is recorded by a 1900*1280 pixels camera (50Hz acquisition frequency). Using image analysis, the fruit trajectory is recovered and the corresponding velocity components computed. A total of 24 fruits are successfully deposited and the following data refer to 24 trajectories as the one shown in Fig. 9, similar to Fig. 5 from Zhu et al. [26] with sandbags settling in a shear flow.

The vertical profile of streamwise mean velocity along the centerline of the channel in the middle of the test region of about 1m long is measured with a micro-ADV (Acoustic Doppler Velocimeter, from Nortek) and is plotted in Fig. 10. The vertical profiles of streamwise and vertical turbulent intensity (not shown here) appear to fairly match the trend previously presented by Nezu and Nakagawa [14, Fig. 4.9].

4.2 Results

Fig. 10 shows the vertical profile of mean streamwise flow velocity u_x and of the ensemble averaged fruits vertical velocity $\langle v_y \rangle$ and streamwise velocity $\langle v_x \rangle$. It was assessed that these ensemble average velocities converged for sample sizes higher than 20. It appears that:

- The mean streamwise velocity of the flow is about uniform in the center part of the water column (equal to $U_0 = 3.5\text{cm/s}$) and decreases when approaching the bed due to the boundary layer and when approaching the free surface due to the velocity-dip phenomenon, i.e. the maximum velocity appears not at the free-surface, but rather just below it in open-channel flows [14].
- Along the fruits motion (*i.e.* from the free surface to the bed) the ensemble averaged fruit vertical velocity $\langle v_y \rangle$ first increases (for $y/h > 0.75$) and then becomes about constant over the depth, as in the free fall experiments and similarly to measurements from Elkholy and Chaudhry [5]. These observation indicate a balance between weight and vertical hydrodynamic forces in the

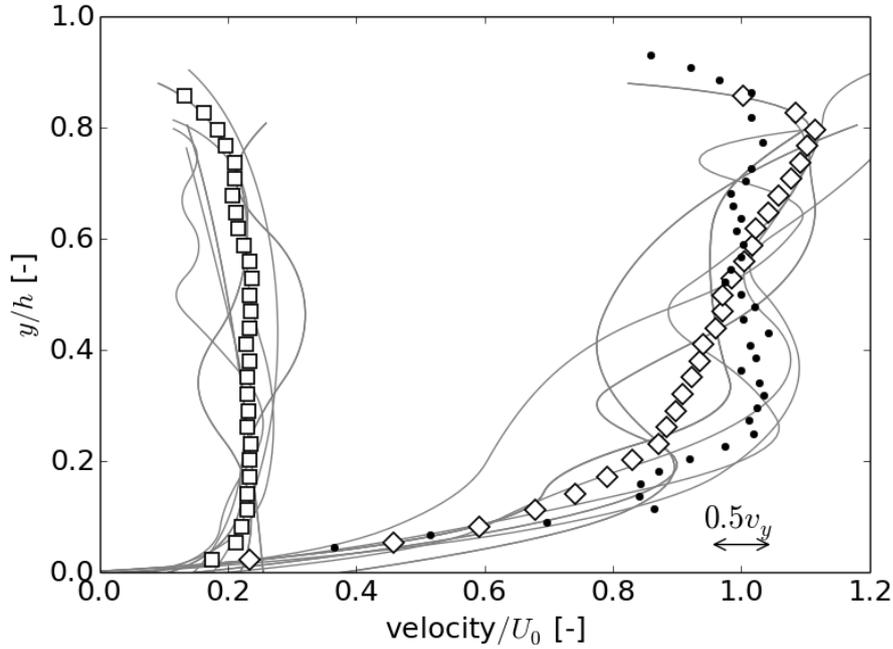


Fig. 10: Dimensionless streamwise flow velocity (u_x : \bullet) plotted along the dimensionless height y/h as well as ensemble average streamwise ($\langle v_x \rangle$: \diamond) and absolute vertical ($\langle v_y \rangle$: \square) fruit velocities, grey solid lines represent the streamwise and vertical velocity of a selection of ten individuals ; $h = 22.0 \text{ cm}$, $U_0 = 3.5 \text{ cm.s}^{-1}$

center part of the channel ($0.15 < y/h < 0.75$). The magnitude of the vertical velocity $\langle v_y \rangle$ is about 0.7 cm/s in the center part of the channel, which is higher than the ensemble average mean settling velocity in water at rest (see Sect. 3.2). This difference of velocity is attributed to the variations of fruit density between the two experiments and the downward secondary current in the center section of the flume. Finally, when approaching the bed, the fruit vertical velocity decreases. This deceleration is attributed to lift forces appearing in the strongly sheared flow close to the bed.

- The profile of ensemble averaged streamwise velocity of the fruits $\langle v_x \rangle$ is qualitatively similar to that of the streamwise flow velocity u_x . However, discrepancies are observed: (i) the fruit velocity gradient is constant in a large portion of the water column ($0.15 < y/h < 0.85$) ; (ii) $\langle v_x \rangle$ exceeds u_x in the upper part of the channel ($y/h > 0.6$) and is smaller in the lower part ($y/h < 0.5$).

In order to investigate the interaction between the flow and the fruits, and thus explain the ensemble average fruit trajectory, it would be useful to compute the lift and drag forces acting on the fruit, based on the measured pathline. This methodology is proposed for instance by Elkholy and Chaudhry [6] on large sandbags. However, estimating exact volume and projected surfaces of the fruits, as well as their density is particularly challenging. The approach selected herein reduces to

the analysis of the velocity of several individual fruits represented by gray lines in Fig. 10.

It appears that:

- The vertical fruit velocity shows a small yet noticeable variability from one fruit to another. The fluctuations of vertical velocity during the fall for a given fruit can be either small or moderate depending on the individual.
- The streamwise fruit velocity shows a large variability from one fall to another and also moderate to large fluctuations during the fall for each fruit. These oscillations are attributed to helical motions as previously observed in the tank with water at rest: the vertical settling velocity produces a horizontal lift force which results in a horizontal circular motion during the settlement. This circular motion alternatively adds or subtracts a streamwise relative velocity to the mean fruit velocity. Hence, the fruit streamwise velocity can alternatively exceed or remain slower than the local flow velocity. It can be seen in Fig. 10 that the fruit streamwise velocity is oscillating around the ensemble averaged value with a difference of velocity of about $0.15U_0$. The tangential velocity of the helical motion was found in Sect. 3.2 to be about $0.25v_y$ which would lead to at most $\pm 0.25v_y$ fluctuations on the streamwise velocity, represented by a double arrow in Fig. 10. Consequently, the streamwise velocity fluctuations for a given fruit are two or three times higher than those measured during free fall. This indicates a complex three-dimensional asymmetric motion of the falling fruits due to the interaction of the helical motion with the one-dimensional turbulent shear flow.

Finally, the main results regarding the streamwise motion obtained in this section are: (i) the ensemble averaged streamwise velocity of the fruits differs from the streamwise velocity of the flow ; (ii) the three-dimensional motion differs from the helical motion in free fall described in Sect. 3.2.

5 Discussion and Conclusion

The typical cycle of a *Fallopia x bohemica* fruit falling on a river surface after it detaches from the tree is to 1) fly in the air, 2) deposit and float on the free surface and 3) sink and 4) eventually deposit. The present work allowed to analyse the behaviours of these achenes as they float and settle in controlled flow conditions. It appeared that the floating time strongly depends on the characteristics of the flow: temperature, agitation and surface tension of the water. The floating time decreases as the temperature increases and as the contact with water increases (through agitation, low surface tension or immersion).

The distances covered by the fruit before it stops and germinates (namely, the mean dispersion length) can be roughly estimated as follows. In the present experiment, the mean floating duration ranges between 14 and 66 hours (see Table 1). In a river with a bulk velocity of 50cm/s , where the surface velocity equals about 62.5cm/s , assuming an average floating time of 40 hours (corresponding to test 1a with strong turbulence and a warm temperature varying between 23 and 28°C), the distance covered by the floating fruit reaches about 90km. However many processes may limit the fruit transport such as a storage in dead zones, in a wake downstream obstacles, in recirculation zones downstream a sudden channel

expansion or upstream a sudden width decrease, which would result in shorter travel distances.

Then, assuming that the river is 2m deep, and that the mean vertical settling velocity equals 0.7cm/s (Fig. 10), the settling duration will be of about 5 minutes (neglecting secondary currents and large scale structures) and the fruit will thus cover a streamwise distance of about 150m. This rough estimate reveals that the distance covered within the water column is negligible compared to the floating distance. As a consequence, in order to fairly estimate the dispersal length of a fruit specie, a knowledge of the floating duration as performed in section 2 is essential. Indeed, as depending on the temperature, agitation, and surface tension, the floating time can vary of about $\pm 100\%$, the mean distance covered by the fruit species varies of the same amount.

Predictive models for the sinking phase would require an estimation of, for instance, drag and lift coefficients of the fruits. Such coefficients are however very dependent on the individual and specie of knotweed, so as on the river flow characteristics. It would be also difficult to account for additional phenomena such as change in river sections, soaking branches, boils, etc. A sinking predictive model was thus not undertaken in the present work, especially as present work clearly shows that the settling time is negligible compared to the floating time. In other words, sinking phase has a negligible influence compared to the floating phase of several tens of hours.

References

1. Andersson, E., Nilsson, C., Johansson, M.: Plant dispersal in boreal rivers and its relation to the diversity of riparian flora. *Journal of Biogeography* **27**(5) (2000)
2. Baskin, C.C., Baskin, J.M.: Seeds: ecology, biogeography, and evolution of dormancy and germination. Elsevier (1998)
3. Chambert, S., James, C.: Sorting of seeds by hydrochory. *River Research and Applications* **25**(1) (2009)
4. Coops, H., Van der Velde, G.: Seed dispersal, germination and seedling growth of six helophyte species in relation to water-level zonation. *Freshwater Biology* **34**(1) (1995)
5. Elkholy, M., Chaudhry, M.: Drag and added-mass coefficients of large sandbags. *Journal of Hydraulic Engineering* **137**(11) (2011)
6. Elkholy, M., Chaudhry, M.: Investigations on the trajectory of large sandbags in open channel flow. *Journal of Hydraulic Engineering* **138**(12) (2012)
7. GISD: Species profile : *Polygonum cuspidatum* Sieb. & Zucc. (= *Fallopia japonica* (Houtt. Dcne.). <http://www.iucngisd.org/gisd/species.php?sc=91> (2016). Accessed: 25-07-2016
8. Grimsby, J., Tsirelson, D., Gammon, M., Kesseli, R.: Genetic diversity and clonal vs. sexual reproduction in *Fallopia* spp. (polygonaceae). *American Journal of Botany* **94**(6) (2007)
9. Hroudová, Z., Moravcová, L., Zákřavský, P.: Effect of anatomical structure on the buoyancy of achenes of two subspecies of *Bolboschoenus maritimus*. *Folia Geobotanica & Phytotaxonomica* **32**(4) (1997)
10. Mandák, B., Bímová, K., Pyšek, P., Štěpánek, J., Plačková, I.: Isoenzyme diversity in reynoutria (polygonaceae) taxa: escape from sterility by hybridization. *Plant Systematics and Evolution* **253**(1-4) (2005)
11. McCutchen, C.: The spinning rotation of ash and tulip tree samaras. *Science* **197** (1977)
12. Nakayama, N., Nishihiro, J., Kayaba, Y., Muranaka, T., Washitani, I.: Seed deposition of *eragrostis curvula*, an invasive alien plant on a river floodplain. *Ecological Research* **22**(4) (2007)
13. Nathan, R.: Long-distance dispersal of plants. *Science* **313** (2006)
14. Nezu, I., Nakagawa, H.: Turbulence in open channels. IAHR/AIRH Monograph. Balkema, Rotterdam, The Netherlands (1993)

15. Praeger, K.: On the buoyancy of the seeds of some britannic plants. The Scientific proceedings of the Royal Dublin Society **XIV** (1913)
16. Probert, R.J.: The role of temperature in germination ecophysiology. Seeds: the ecology of regeneration in plant communities. CAB International, Wallingford, UK pp. 285–325 (1992)
17. Ridley, H.: The Dispersal of Plants Throughout the World. Kent, L. Reeve & Company (1930)
18. Rouifed, S., Puijalon, S., Viricel, M.R., Piola, F.: Achene buoyancy and germinability of the terrestrial invasive *Fallopia x Bohemica* in aquatic environment: A new vector of dispersion? *Ecoscience* **18**(1) (2011)
19. Sculthorpe, C.: The biology of aquatic plants. Edward Arnold Ltd., London (1967)
20. Skoglund, S.: Seed dispersing agents in two regularly flooded river sites. *Canadian Journal of Botany* **68**(4) (1990)
21. Sridhar, M., Reddy, C.R.: Surface tension of polluted waters and treated wastewater. *Environmental Pollution Series B, Chemical and Physical* **7**(1), 49–69 (1984)
22. Tiébré, M.S., Bizoux, J.P., Hardy, O., Bailey, J., Mahy, G.: Hybridization and morphogenetic variation in the invasive alien *Fallopia* (polygonaceae) complex in belgium. *American Journal of Botany* **94**(11) (2007)
23. Varshney, K., Chang, S., Jane Wang, Z.: Unsteady aerodynamic forces and torques on falling parallelograms in coupled tumbling-helical motion. *Physical Review E* **87** (2013)
24. Yang, C.: *Sediment Transport: Theory and Practice*. McGraw-Hill, New York (1996)
25. Yoshikawa, M., Hoshino, Y., Iwata, N.: Role of seed settleability and settling velocity in water for plant colonization of river gravel bars. *Journal of Vegetation Science* **24**(4) (2013)
26. Zhu, L., Wang, J., Cheng, N., Ying, Q., Zhang, D.: Settling distance and incipient motion of sandbags in open channel flows. *Journal of Waterway, Port, Coastal and Ocean Engineering* **130**(2) (2004)