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Development of a flatbed passive integrated transponder antenna grid for continuous monitoring of fishes in natural streams

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This paper describes a flatbed antenna grid designed for continuous remote monitoring of fish tagged with 23 mm passive integrated transponder (PIT) tags in a natural stream with extensive spatial coverage. A range of applications of the system is presented.

Key words: Atlantic salmon; movements; PIT tags; *Salmo salar*.

Passive integrated transponder (PIT) technology is increasingly being used to monitor the behaviour of freshwater fishes in both experimental and natural settings. This technology is versatile because PIT tags are small, inexpensive, last indefinitely and allow the individual identification of fishes. Early PIT systems were developed mainly for the continuous monitoring of fishes in fixed experimental settings or through hydroelectric facilities and fishways (Prentice *et al.*, 1990; Brännäs *et al.*, 1994; Armstrong *et al.*, 1996; Castro-Santos *et al.*, 1996; Burns *et al.*, 1997). Portable PIT detectors were then developed to allow the monitoring of fish distribution over a larger spatial extent in wadable streams (Morhardt *et al.*, 2000; Roussel *et al.*, 2000; Zydlewski *et al.*, 2001; Cucherousset *et al.*, 2005; Hill *et al.*, 2006; Linnansaari & Cunjak, 2007; Linnansaari *et al.*, 2007). Portable systems have nevertheless a limited temporal resolution compared to stationary systems because they must be operated manually by a person wading the stream, which is potentially disruptive for the fishes as well as making the task to survey a study section labour intensive and time consuming, thereby restricting the possible frequency of surveys. Recent developments in PIT systems have combined the advantages of both stationary and portable systems by adapting stationary, single and multiple,

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antennae systems to natural environments for continuous monitoring of fishes with higher spatial and temporal resolution (Armstrong *et al.*, 1996, 1999; Greenberg & Giller, 2000; Morhardt *et al.*, 2000; Zydlewski *et al.*, 2001, 2002; Riley *et al.*, 2003; Ibbotson *et al.*, 2004; Teixeira & Cortes, 2007).

The trade-off between accuracy in the location of the tag, spatial coverage, detection range and temporal resolution is dependent on the limitations inherent to the technology used to build the systems. An important aspect in the design of PIT systems is the choice of full duplex (FDX) or half duplex (HDX) technology. FDX transceivers send and receive signals simultaneously, whereas HDX transceivers send and receive signals to and from the tag asynchronously. Therefore, FDX systems are inherently faster but also more energy consuming compared to HDX systems. The size of the tag also has a great influence on the performance of PIT systems with large tags being detectable from farther away. Typically, FDX systems are used with 12 mm tags and achieve a detection range varying between 20 and 360 mm (Brännäs *et al.*, 1994; Armstrong *et al.*, 1996; Ibbotson *et al.*, 2004; Cucherousset *et al.*, 2005; Teixeira & Cortes, 2007), which can be increased to 900 mm with the use of larger FDX tags (*i.e.* 23 mm) and specific antenna designs (Hill *et al.*, 2006). Nevertheless, the short detection range of most FDX systems has been cited as being the main impediment to study fish behaviour in natural settings and improving the antennae or using larger tags has been suggested as a solution to broaden the application of PIT technology (Brännäs *et al.*, 1994; Armstrong *et al.*, 1996; Greenberg & Giller, 2000; Zydlewski *et al.*, 2001; Riley *et al.*, 2003; Teixeira & Cortes, 2007). Larger tags, however, have to be implanted in relatively large fishes (>84 mm fork length, L_F) (Roussel *et al.*, 2000) in order to minimize possible adverse effects on growth and survival.

HDX systems used with large 23 or 32 mm tags can offer a detection range of 1000 mm either with portable or stationary equipment (Castro-Santos *et al.*, 1996; Roussel *et al.*, 2000; Zydlewski *et al.*, 2001; Linnansaari & Cunjak, 2007; Linnansaari *et al.*, 2007). Zydlewski *et al.* (2001) developed a stationary cross-river HDX system to record the longitudinal movements of marked fishes (with 23 mm tags) in a 8 m wide stream. This system scanned the entire water column at all discharges without disrupting fish movements, overcoming many of the previous limitations regarding the use of PIT systems in natural streams. While cross-river antennae enable the study of large-scale longitudinal movements, antenna grid systems that allow the study of fish space use over extended areas and with high spatio-temporal resolution need to be developed. This paper describes a flatbed antenna grid designed for continuous remote monitoring of PIT-tagged fishes in a natural stream at an intermediate spatial scale (*i.e.* reach scales *c.* 100 m).

The flatbed antenna grid is an antenna array buried underneath the bed surface of a stream. It consists of 242 HDX antennae that detect 23 mm PIT tags [Texas Instruments (TIRIS) model RI-TRP-RRHP, 134·2 kHz: Texas Instruments; www.ti.com] and other tags complying with the ISO 11784/11785 international standards. The antennae are connected to tuning capacitors units with 5 m long twin-axial wires (possible maximum distance: 10 m) [Fig. 1(a)]. The tuning units are in turn linked to a CYTEC multiplexer (JX/256 series; mercury

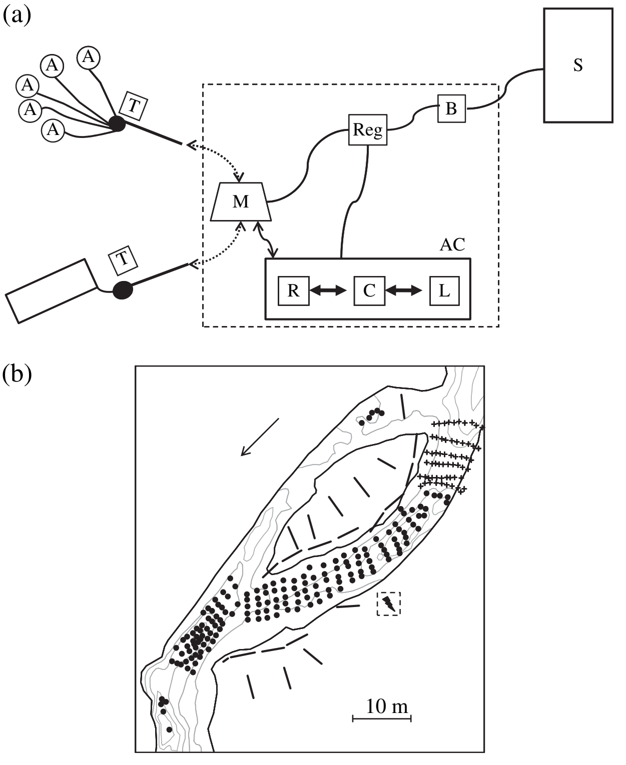

FIG. 1. (a) Schematic diagram of the electronic system. Round and rod antennas (A) are connected in groups of five to a tuning capacitor units (T), while rectangular antennas have their own tuning units, which are in turn connected to a multiplexer (M). The multiplexer (M) is linked to the Aquartis controller (AC) containing an Aquartis controller (C), a TIRIS reader (R) and a datalogger (L). The multiplexer and the Aquartis controller are both connected to a DC converter (Reg) linked to the batteries (B) and solar panels (S). The multiplexer, Aquartis controller, DC converter and batteries are housed inside a shelter (dotted box). Arrows indicate the flux of information. (b) Map of the study site with the location of the antennas with round (●), rectangular (—) and rod (+) antennas. Isocontours of water depth at a discharge of $0{\cdot}07\ m^3\ s^{-1}$ are displayed each 200 mm. Arrow indicates flow direction. The dotted box represents the shelter containing the electronic components (not to scale).

wetted 256 single poles relay; www.cytec-ate.com) either using cables composed of 10 multistrand wires (gage 22) for round and rod antennae or using twin-axial wires for rectangular antennae [Fig. 1(a)]. In this system, the longest cable is 60 m but it could be as long as 200 m if a greater distance from the multiplexer was required. The multiplexer is connected to an Aquartis controller (custom made by Technologie Aquartis; www.aquartis.ca) composed of a TIRIS S-2000 reader (composed of high performance RA-RFM unit RI-RFM-008B and control module RI-CTL-MB2A; Texas Instruments), a datalogger and a custom-made controller unit. This unit manages the flux of information between the multiplexer, the RFID system (TIRIS reader) and the datalogger. The 75 W of power required by the system is provided by three 110 W solar panels linked to four 6 V rechargeable batteries connected in series, and to two 12 V deep-cycle marine batteries connected in parallel. Nonetheless, the number of batteries needed is dependent on the solar radiation available (*i.e.* photoperiod length and intensity) and the location of the panels, thus, a variable number of batteries could be used depending on the context. When a tag is detected by any of the antennae, the date (dd/mm/yy), time (hh:mm:ss), antenna ID (multiplexer card and port number) and fish ID (tag number) are recorded on a 1 GB SD card. All antennae in the system are activated sequentially requiring 120 ms per antenna. The interrogation of all the antennae (*i.e.* multiplexer ports) requires 33 s.

Most antennae in the grid ($n = 160$) are round antennae of 500 mm in diameter. They are made of PVC tubing, enclosing three loops of multistrand wire (guage 10, insulated copper wire). Reading range varies depending on the tag orientation and position. The maximum detection range achieved with this type of antenna is 400 mm in height and 800 mm in diameter on the horizontal plane when holding the tag perpendicular to the antenna. When the tag is held horizontally, the range is reduced to 300 mm in height by 600 mm in diameter. Tags positioned exactly in the centre and parallel to the antenna plane cannot be detected due to the normal 'blind spot' in the detection field (Linnansaari *et al.*, 2007). The second type of antennae are 3×1 m rectangular antennae ($n = 22$) built to cover a larger area than round antennae. These antennae are made with two loops of multistrand wire (guage 10, insulated copper wire) and achieve a detection range of 400 mm vertically. The third type of antennae ($n = 60$) are 200 mm long manganese–zinc ferrite rods (magnetic permeability adapted to a frequency of 134·2 kHz: $\mu = 850$) composed of a coil encapsulated in PVC tubing. The rod antennae were designed for easy installation in stream areas with coarse substratum, but they have a smaller detection range (*i.e.* 200 mm) than the other two antennae types. Interference problems were, however, experienced with these antennae at installation.

The flatbed antenna grid was installed in a natural stream in summer 2006 and was used to study fish movements in 2007. The Ruisseau Xavier, a 4 km long tributary of the Sainte-Marguerite Nord-Est River, Québec, Canada, (48°25′17″ N; 69°53′48″ W), was selected for installing the antenna grid. The tributary is a second order stream of *c.* 10 m in width, composed of short riffle-pool sequences in its lower part where the system was installed. The site chosen for the antenna grid is a 100 m long section of the stream located 425 m from its confluence with the main river. The site is composed of a main and a secondary channel separated by a gravel bar flooded during high flows [Fig. 1(b)]. The substratum varies from cobble–boulders in the riffles to sand–gravel in the pools, and the maximum depth is 1·5 m at the median discharge of 0·46 $m^3 s^{-1}$.

The antenna grid was installed in late August to early September 2006 at low flow. Prior to the installation of the antennae, fishes were removed from the study section by electrofishing. They were kept in flow-through enclosures, and put back in the stream after the installation was completed (*i.e.* 1 week). The antennae were buried flat *c.* 150 mm beneath the riverbed armour layer in order to resist most flow conditions. A small excavator was used to dig furrows where the antennae and wires were buried. Substratum disturbance was minimized by proceeding with one antenna line at a time and by covering the antennae with the substratum previously displaced when digging. The armour layer of the substratum was put back in place manually to recreate the original configuration and to ensure substratum stability by recreating the imbrication. The structure of the study site did not appear visually different from its original state after the installation of the antennae. It took a team of six people 7 days to build the antennae and an additional 7 days to complete burying the antennae in the streambed. Another 2 weeks and two people were needed to complete the configuration and tuning of the system. Costs are directly proportional to the spatial extent and geometrical configuration of the system because it determines the length of cables needed.

The three different antenna types were distributed to cover the largest possible area of the stream section [Fig. 1(b)]. Round antennae were positioned in the low-flow wetted area of the stream. Rectangular antennae were buried along the wetted perimeter to monitor fish movements in case of extended flooding, and one rectangular antenna was used to cover the upstream access of the secondary channel. Rod antennae were located at the upstream end of the study site. All antennae were positioned with sufficient distance from each other to avoid detecting tags on two antennae at the same time, but to minimize gaps where no detection was possible. Nevertheless, interference between rod antennae was found to be unexpectedly high after installation (due to single pole relays); therefore, they were never activated for studying fish movements. The section covered with antennae was thus shorter than originally planned, but the free ports on the multiplexer were used to add antennae in the secondary channel ($n = 5$) and in the downstream pool ($n = 5$) where many fishes were seen when snorkelling in summer 2007. After the installation was completed, the antennae were georeferenced with a total station. It was thereafter possible to interpolate fish positions by converting antenna ID into spatial co-ordinates. Overall, the detection field of the antenna grid covered 27% of the wetted area of the site at a discharge of $0{\cdot}07\ m^3\ s^{-1}$. All electronic components were contained in a shelter constructed on the riverbank, outside of the immediate flood zone of the stream [Fig. 1(b)].

The antenna grid was used to record the movements of PIT-marked juvenile salmonids from 17 July to 19 November 2007. Fishes were captured in the study site by electrofishing on 3 July and 4 September 2007. All fishes >95 mm L_F were PIT tagged with 23 mm tags (Texas Instruments), for a total of 36 juvenile Atlantic salmon *Salmo salar* L. (July: $n = 26$ and September: $n = 10$) and 17 juvenile brook trout *Salvelinus fontinalis* (Mitchill) (July: $n = 9$ and September: $n = 8$). The minimum size for tagging was determined using the study of Roussel *et al.* (2000), which suggested tagging fishes >84 mm L_F to avoid mortality, and on the study of J.-N. Bujold (unpubl. data) who suggested a minimum of 95 mm L_F to avoid effects on growth of juvenile *S. salar*.

The maintenance of the system was minimal. Every week, two of the batteries powering the antenna system were changed for fully charged ones in order to avoid power failures. A control tag was placed on an antenna located on the bank to ensure that the system was continuously recording fish positions. The memory card was downloaded at least once a week, and the data were verified for any interruptions or irregularities. Some delays in the scanning cycle were attributed to interferences with electronic equipment used by the park warden working in the area. Occasional power breakdowns occurred but never lasted for more than a few hours at a time. They were due to cloudy conditions and a diminishing photoperiod in late autumn limiting the solar radiation needed to charge the batteries. The system was configured to restart itself when enough power was available to turn on both the multiplexer and the Aquartis controller.

The antenna grid generated 128 903 detections over the whole study period. A total of 49 of the 53-tagged fishes (93%) were detected at least once on the antenna grid. Most individuals were detected numerous times with a mean of 3173 detections per individual and a maximum of 26 811. Such a high number of detections was obtained because some individuals were constantly using areas with high density of antennae or were hiding in the substratum covering the antennae. MATLAB® (version R2007a; MathWorks Inc., www.mathworks.com) programmes were used to handle the large database generated by the antenna system.

There are many advantages in using this antenna grid system. The main advantage is the continuous remote monitoring of juvenile salmonids with high spatial and temporal resolution. The presence of an antenna nearly every 5 m^2 in the 100 m long study section provides a high scope or ratio of extent to grain size (Schneider, 2001). A high scope increases the ability to detect patterns across a range of scales by having many sample points, each covering a small area or volume (grain), with high sampling frequency over a relatively large area (extent). A complete record of fish positions over a 4 months period was obtained, allowing the potential description of habitat use, movements, home ranges and activity patterns of individuals on a diel, day-to-day and on a seasonal basis. As far as is known, this is the first time a system was developed to monitor fish positions *in situ* over extended areas, with high resolution and with the ability to collect data consistently over a 4 month period.

With this system, individual fishes' use of space can be monitored with high spatial resolution and integrated at a relevant scale. For example, the precise positioning of fishes can allow the study of microhabitat selection given a prior surveying of the physical variables surrounding the antennae of the grid. Mobility patterns can also be inferred as the timing of movements from one antenna to another is recorded [Fig. 2(a)]. With each antenna activated every 33 s and 27% of the wetted area covered, the spatial location of fishes cannot be explicitly known at all times for the whole population, but some very relevant interpretation can be carried out. Variations in habitat use can be examined over a desired time frame by computing home ranges, mean positions [Fig. 2(b)] and probability density functions of fish locations. The antenna grid can be a useful tool to gather information about how the physical structure of a stream (*e.g.* depth, velocity, substratum and woody debris) affects patterns of habitat use and mobility. For example, comparing the use of riffles *v.* pools, day *v.* night microhabitat selection or seasonal changes between summer and winter habitats. In addition, the monitoring of fish behaviour in changing habitat conditions can be performed. Fish movements at high flows or during ice cover formation could also be recorded, providing fundamental information on mobility patterns when other sampling methods cannot be used.

Another interesting application of the antenna grid is the study of the activity patterns of fishes (Fig. 3). The number of movements made by one or many

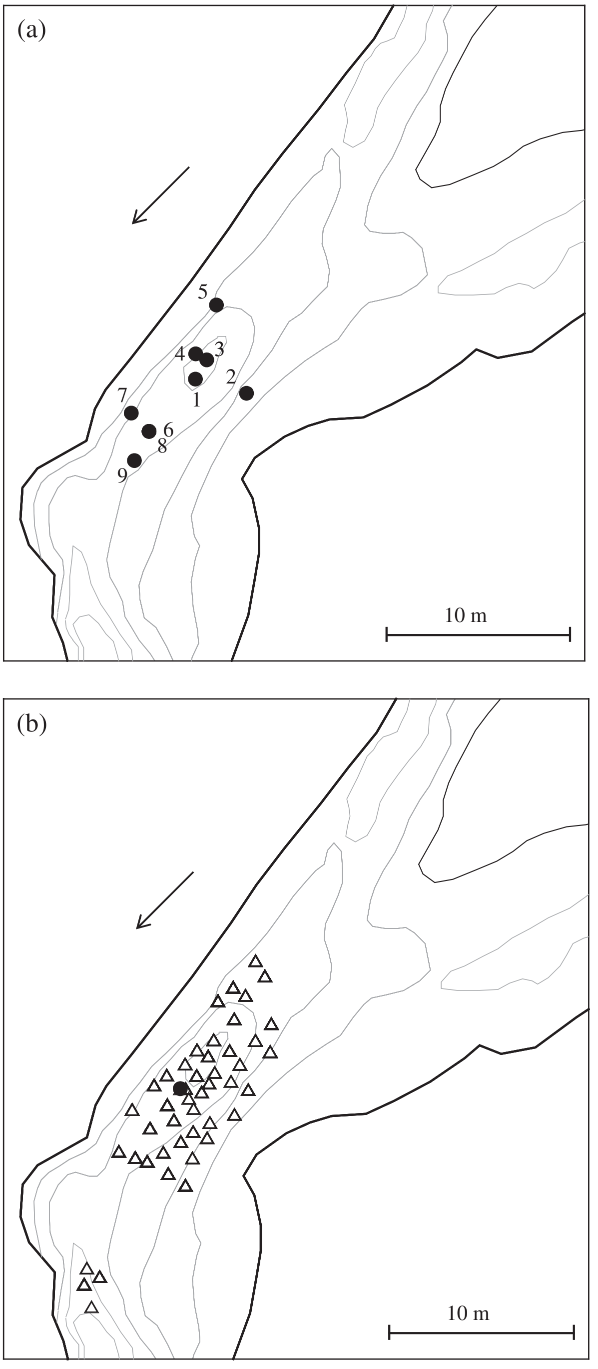

FIG. 2. Spatio-temporal dynamic of habitat use of a selected juvenile *Salmo salar*, with (a) successive night-time positions (●) on 27 July 2007, at (1) 000747, (2) 000807, (3) 000808, (4) 012147, (5) 012730, (6) 020409, (7) 022547, (8) 023210 and (9) 040813 hours. (b) Night-time (△) positions over the whole study period with associated mean position (●) inferred from the spatial co-ordinates of the positions ($n = 3968$).

individuals over the diel cycle can be calculated for specific days [Fig. 3(a)] or integrated over a time interval [Fig. 3(b), (c)], providing detailed information on the behaviour of individuals. In addition, visual observations of fish activity can be made in order to determine if the fishes are active in the water column or if they are hiding. Interindividual variations in time budgeting, for example diurnal *v.* nocturnal foraging strategies, and associated consequences on performance in terms of growth or survival can be studied if additional sampling of fish condition is carried out.

The detection range of this HDX system is greater than that of multiple antenna systems previously used in the field that relied on the FDX transmission mode (Armstrong *et al.*, 1996; Greenberg & Giller, 2000; Riley *et al.*, 2002, 2003; Teixeira & Cortes, 2007). With a vertical detection range of 400 mm, half of the antennae cover the entire water column at low flow, while the other half located in deeper areas cannot encompass it entirely. Because juvenile *S. salar* have a tendency to stay close to the substratum when moving in fast-flowing water (Armstrong *et al.*, 1996), the proportion of fish swimming higher than 400 mm from the bottom in deeper sections is assumed low but could not be evaluated. Further developments in PIT systems should include improvement of the detection range to enable their use in larger rivers or to broaden their application to the study of fishes moving higher in the water column.

The inability to distinguish two fishes in the same antenna field at the same time is a limitation of PIT systems (Armstrong *et al.*, 1996; Castro-Santos *et al.*, 1996; Burns *et al.*, 1997; Greenberg & Giller, 2000; Morhardt *et al.*, 2000; Zydlewski *et al.*, 2001; Ibbotson *et al.*, 2004; Linnansaari *et al.*, 2007) and is an important concern especially when tracking fishes in high-density areas or shoaling species. The use of many small antennae helps to reduce the probability of having several fishes in the same antenna field simultaneously. If fishes are moving, there is a high probability that they will either be detected sequentially by the same antenna or that they will be detected by concomitant antennae. Tag collision (*i.e.* multiple tags blocking the detection of each other) did not appear problematic in the context of tracking juvenile salmonids with the flatbed antenna grid. Errors in reading tag codes due to collision or interference were 0·07% of the data recorded. Moreover, during the frequent snorkelling and portable antenna surveys made in the study section in summer to autumn 2007 (P. Johnston, unpubl. data), more than one fish was never located on a given antenna. Some individuals were, however, found sheltering in the substratum over the same antenna for long periods, which certainly prohibited the detection of other fishes passing by but allowed the study of activity patterns of the hiding fish. The application of this system for other fish species displaying different social behaviour needs further evaluation.

The antenna grid system presented here offers a compromise between spatial resolution, spatial extent and detection range. Smaller antennae could have increased the spatial resolution but a larger number of them would have been required to achieve a similar spatial extent. On the other hand, increasing the number of antennae reduces sampling rate and thus the temporal resolution. Finally, detection range could be increased by using larger antennae but at the expense of the spatial resolution. In this antenna grid, the spacing between antennae is sufficiently small to allow the study of microhabitat use, yet the 242

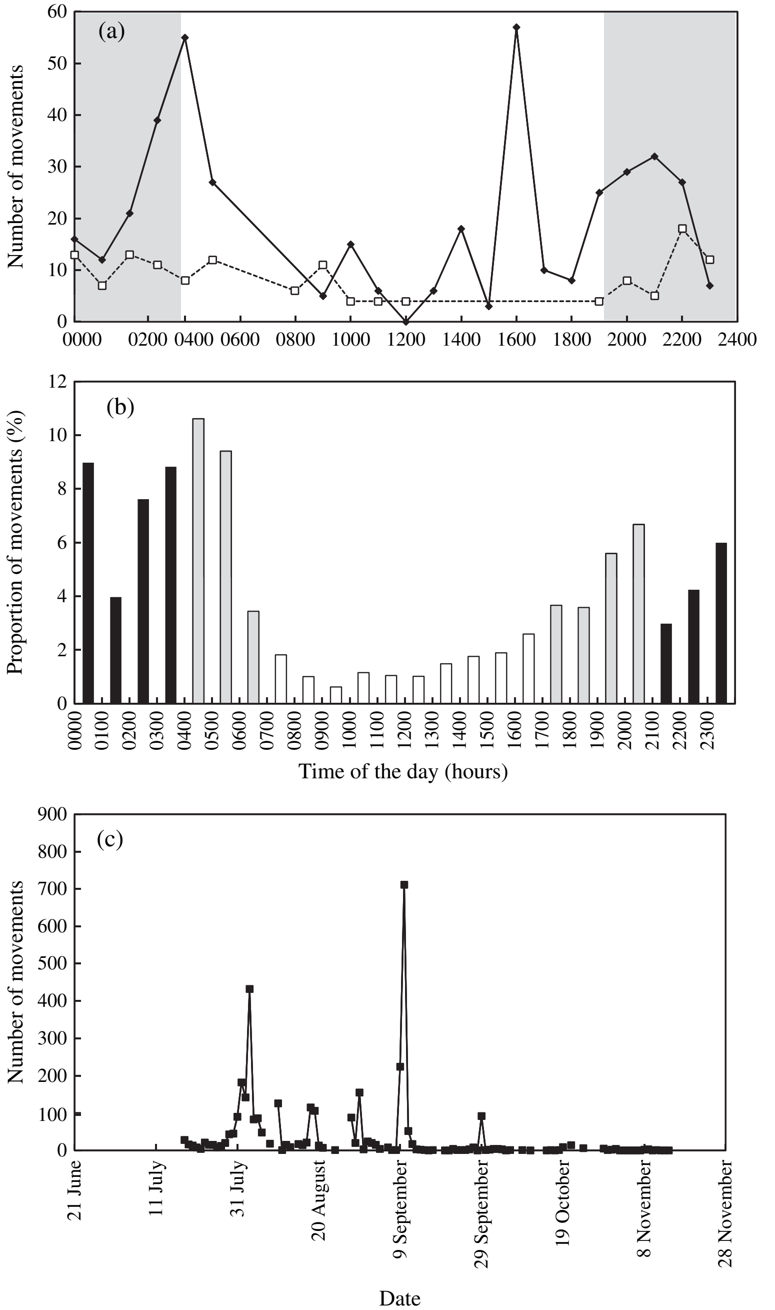

FIG. 3. Daily temporal dynamic of movements. (a) Activity levels expressed as the number of movements for a selected fish per hour for 2 days, 1 (–◆–) and 2 (-□-) August 2007. The grey zones indicate night-time. (b) Activity levels expressed as the proportion of movements per hour of the day for all detected *Salmo salar* over the whole study period (■, night-time; □, daytime and ▒, the period of changing luminosity throughout the study period). (c) Total number of movements per day for a selected fish over the whole study period.

antennae cover a surface large enough to enable the recording of larger movements. With a single multiplexer (of this particular model), it is nevertheless possible to have a maximum of 256 antennae and to cover a 400 m longitudinal extent, *i.e.* 200 m on each side of the multiplexer due to the maximum distance at which the tuning units can be located. The spatial coverage could be considerably extended by using many multiplexers because there are no limitations regarding the number of multiplexers that can be used in parallel.

An important question in ecology is how fishes respond to the high temporal and spatial variability of habitat conditions in streams. The use of PIT systems allows the gathering of empirical data on individual behaviour that is needed to understand population ecology and how individual behaviour translates into population dynamics (Greenberg & Giller, 2000). Multiple antenna PIT systems, such as the one presented here, enabling the study of fish movements at different time frames and spatial scales, have the potential to provide crucial information on habitat use, biotic interactions (competition and predation) and movements of stream fishes.

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