Automating Data Collection in Motor-manual Time and Motion Studies Implemented in a Willow Short Rotation Coppice

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Time and motion studies are often used to evaluate the performance of various product systems. However, traditional studies are characterized by a series of technical limitations, and they require many resources. This study tested the capability of a low-cost Global Positioning System (GPS) receiver and an accelerometer unit to automate the field data collection for characterizing motor-manual felling of willow short rotation coppices. The results were promising. By thresholding the acceleration data, the running and stopped engine states were accurately separated. Also, by combining the GPS speed with the acceleration data, followed by threshold setting and data visualization in the Geographic Information System software, detailed time categories, such as productive, working, and non-working times, could be separated. The methods described herein could be used to manage long-term field data collection, as such operations are affected by many operational factors.

Keywords: Automation; Global positioning system; Accelerometer; Thresholding; Geographic information system; Willow; Short rotation coppice; Motor-manual; Harvesting

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INTRODUCTION

The study of time and motion is one of the most highly used research tools for evaluating the performance of various technical systems. In systems designed and implemented to procure lignocellulosic biomass for various applications, such studies are implemented to understand the behavior of the productive performance of the equipment relative to the variation in the working conditions (Visser and Spinelli 2012). The goal of these studies is to match the capabilities of the machines with their operational environments and to evaluate the environmental performance of a system or piece of equipment in terms of the energy inputs and potentially harmful outputs such as greenhouse gases emissions (Picchio *et al*. 2009; Balimunsi *et al*. 2012; Heinimann 2012; Maesano *et al*. 2013; Vusić *et al*. 2013; Ignea *et al*. 2016; Ackerman *et al*. 2017). This is done as a measure to choose the best technical option or to obtain detailed overviews of the time consumption categories required to develop work and cost rating systems (Toupin *et al*. 2007), which helps in the optimization of the systems in question (Ghaffaryian *et al*. 2010; Jourgholami *et al*. 2013). To this end, modeling studies are able to provide detailed elemental data (Borz *et al*. 2014b) and empirical relations required for optimization tasks. Similar approaches are used to perform such studies both in traditional forestry and short rotation coppice (SRC), as is shown by many recent studies.

Several methods, techniques, and procedures are currently used to conduct time studies. The traditional methods are based on manual approaches and are characterized by a series of limitations (Borz *et al*. 2014a; Contreras *et al*. 2017), including the need to use many trained people to collect field data (Borz and Ciobanu 2013; Borz *et al*. 2013). Such people need to focus their attention on collecting time inputs, operational variables, and production outputs. This requires a substantial measurement effort and may cause errors. Nevertheless, traditional studies are considered to be the backbone of forestry-related production studies (Heinimann 2007) and are still used in many parts of the world. In contrast, modern techniques have shown a great potential in automating parts of typical tasks in such studies. For instance, video recording approaches using devices able to capture and store digital data have enabled the automation of field data collection and can detail the real sequence of the operations being surveyed (Borz *et al*. 2014a; Apăfăian *et al*. 2017; Contreras *et al*. 2017). Video recording approaches are also used to validate the results of other approaches for studying time (McDonald *et al*. 2001; McDonald and Fulton 2005; McDonald *et al*. 2008). Nevertheless, data processing at the office, where researchers need to play the files and extract the elemental time consumption, is still labor intensive. Recent studies have shown that the amount of time spent on such tasks depends on the study design and complexity, and it can be two to six times greater than the length of the captured video files (Borz and Adam 2015; Mușat *et al*. 2015). In contrast, sensor-based studies are characterized by a promising potential to automate field-data collection and partly substitute the human intelligence required for separating and extracting meaningful data (Borz 2016; Cheţa and Borz 2017). Coupled with other data collection means, they can add self-data collection capabilities to a given machine or tool, including measurements of the fossil energy inputs (Talagai and Borz 2016). Usually, fossil energy inputs are used to evaluate the environmental performance of lignocellulosic biomass procurement (Picchio *et al*. 2009; Balimunsi *et al*. 2012; Heinimann 2012; Maesano *et al*. 2013; Vusić *et al*. 2013; Ignea *et al*. 2016; Ackerman *et al*. 2017), and their amount is dependent on the engine running time (Vusić *et al*. 2013). Therefore, by using such approaches, one could simultaneously obtain meaningful data on the operational and environmental performance of a given system. At the same time, finding ways to exclude the presence of researchers in the field has many benefits related to financial resources, data accuracy, and work safety, as well as preventing observer bias (Acuna *et al*. 2012).

The Global Positioning System (GPS) has the capability to document the equipment movement, and it has been used in both traditional forestry (McDonald *et al*. 2001; McDonald and Fulton 2005; McDonald *et al*. 2008; Borz *et al*. 2015; Strandgard and Mitchell 2015) and SRC (Eisenbies *et al*. 2014; Bush *et al.* 2015) to perform time and motion studies. While there are many solutions and devices on the market, research has shown that low-cost, consumer-grade GPS receivers are able to procure very accurate data, even when the motion speed is low (Keskin and Say 2006). Study approaches that couple acceleration sensors with a GPS system have been successfully used to document other features that could not be collected using GPS alone, for both manual (McDonald *et al*. 2008) and fully mechanized equipment (Strandgard and Mitchell 2015).

Because of specific operational management, the establishment of SRC plantations has more in common with agriculture than forestry (van der Meijden and Gigler 1995; Tubby and Armstrong 2002). Harvesting operations are done by implementing either a cut-and-chip or cut-and-store system (Vanbeveren *et al*. 2015), with the latter being performed using a chainsaw (Burger 2010; Schweier and Becker 2012) or brush cutter (Talagai *et al*. 2017). In general, motor-manual operations done by brush cutters have been shown to be characterized by an intensive amount of physical work (Toupin *et al*. 2007) and increased delivery costs (Vanbeveren *et al*. 2015). Nevertheless, motor-manual equipment is better fitted and is still widely used in small-scale willow SRC cut-back and harvesting operations (Talagai *et al*. 2017) or in cases where fully mechanized equipment is not available (Vanbeveren *et al*. 2015). Such contexts are typical of traditional forestry in Eastern European countries, including Romania (Rauch *et al*. 2015; Moskalik *et al*. 2017), and probably also willow SRC because such practices are relatively new in the area (Scriba *et al*. 2014).

When using a brush cutter to perform felling operations in a willow SRC, the traditional time and motion studying techniques are labor intensive because they require at least one field researcher (Talagai *et al*. 2017) to monitor the operations and capture time consumption data, which is something that can only be achieved by following the harvesting crew during the operation; this requirement may further expose the researcher to safety hazards. Additionally, the use of the snapback chronometry method (Björheden *et al*. 1995), which can save time during data processing tasks, is technically limited because of the prospective appearance of very short quick-changing events. Moreover, operational variables need to be collected, such as those that characterize the row lengths and biomass production (Talagai *et al*. 2017). These tasks require the presence of additional research personnel. At the same time, various events can characterize a time study and influence time consumption during motor-manual harvesting operations in willow SRCs. Moving with the engine running while felling, moving with the engine running without felling, headland turns, delays (at the headlands or within the land), and time spent to replace the felling discs or to refuel the tool are typical examples of such events. In particular, a separation of the running and stopped engine states is important from a time consumption standpoint because such states are likely to characterize the operation and nonoperation events. Also, the operation time is related to the fuel and energy intake.

The goal of this study was to test the capability of an acceleration sensor coupled with a low-cost GPS receiver to automatically collect meaningful time and motion data during motor-manual willow SRC felling operations using a brush cutter. In particular, the authors wanted to test the capability of the studied system to distinguish between the running and stopped engine states, and also test its capability to distinguish between specific work elements.

EXPERIMENTAL

Motor-manual felling operations using brush cutters were done on the 27th of February, 2017 in a willow SRC located near Poian, Covasna county, Romania. The owner of the SRC uses this plantation also to procure regeneration material, which means that each year he harvests smaller plots to manufacture the cuttings needed for the establishment of other SRCs. In such cases, the typical procurement operations are motor-manual felling, followed by manual bunching and hauling to a storage facility where the cuttings are manufactured. Operations were performed on a 0.5-ha plot (plantation scheme of 0.75 m between rows and 1.50 m between twin rows) located at 46° 04’ 21” N - 26° 10’ 55”, 580 m above sea level on flat land (Fig. 1), using a Husqvarna 545 RX brush cutter (Husqvarna AB, Stockholm, Sweden) equipped with a steel saw blade (Fig. 2) with a crew consisting of two men. The operations were monitored for a full working day during which the crew managed to operate all of the area designated as the study plot.

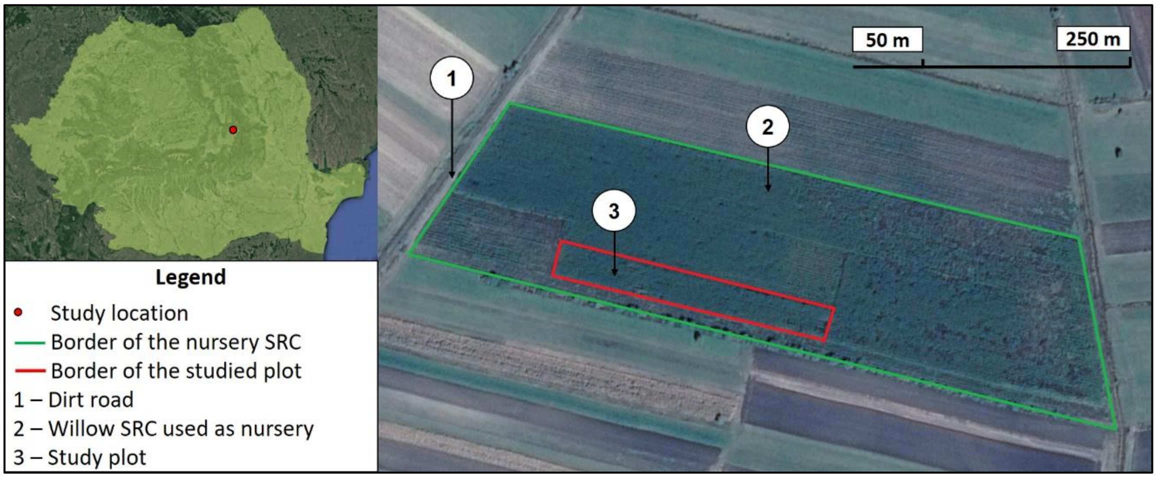

Fig. 1. Study location

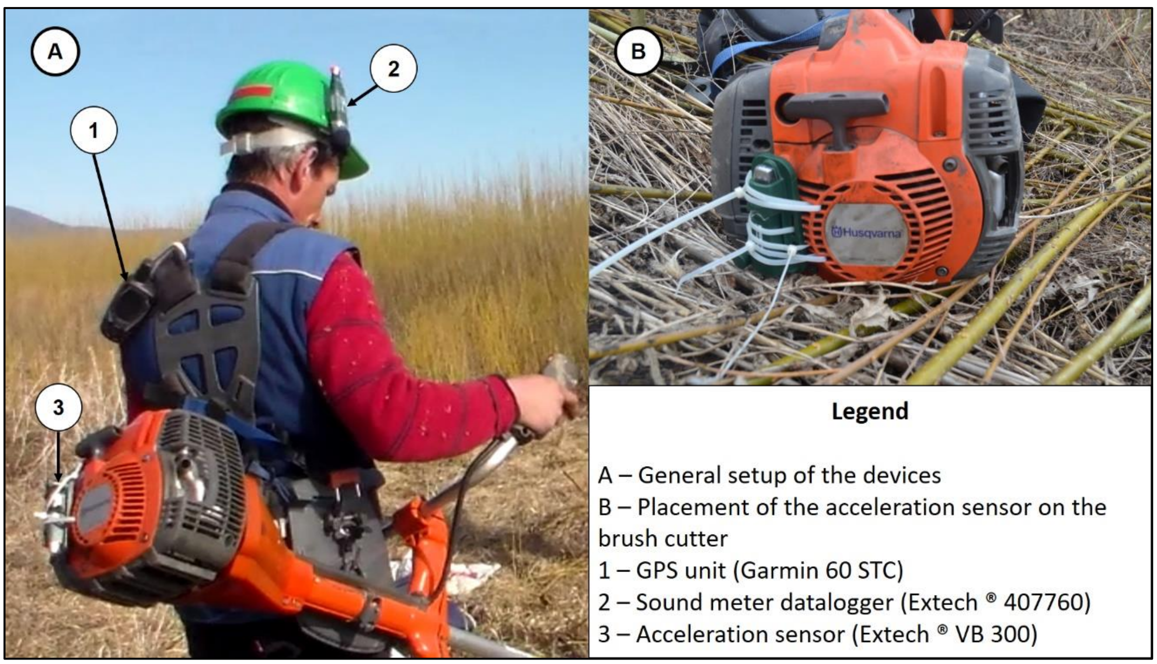

Fig. 2. Placement of the dataloggers: A: general setup and B: acceleration sensor placement

An Extech® VB 300 vibration and motion detection datalogger (Extech Instruments, FLIR Commercial Systems Inc., Nashua, NH, USA) was placed on the engine of the brush cutter in a location that avoided obstructing the usual way of working. Such dataloggers are able to collect accurate (± 0.5 g) three-axis acceleration data in the range of plus or minus 18 g at a sampling rate that ranges between 500 milliseconds for online sampling and 24 h for outline sampling that is stored on a 4-Mb internal memory. A key characteristic of the datalogger used is its reduced size (95 mm × 28 mm × 21 mm) and weight (20 g), which eliminates the carrying burden and makes it feasible for motor-manual studies. Additionally, the setup and data downloading tasks were supported by dedicated software that enables the adjustment of the sampling rate, as well as data visualization and exporting to MS Excel (Microsoft, Redmond, USA). In this study, the highest available offline sampling rate (1 s) was used. A Garmin 62 STC GPS unit (Garmin Ltd., Olathe, USA) was used to document the movement data. For the sake of data processing efforts and because of the slow movement characteristics of similar operations (Talagai *et al*. 2017), this study used a sampling rate of 5 s for the positioning data.

Both the GPS and acceleration sensor are capable of detailed data documentation, including the use of date and time labels paired with the sampled features. This capability was used to pair the clocks of the devices prior to their setup with a portable computer. The GPS and acceleration sensor were started manually at the same time, and then placed on the brush cutter engine and strap, respectively. After placement of all of the devices, the workers were instructed to perform their tasks as usual, and the operations were videotaped as they progressed. At the end of the day, the devices were taken off of the equipment and the datalogging was switched off simultaneously on both devices.

The positioning data was downloaded to a computer as a .GPX file using regular data transfer procedures. It was then uploaded into the Base Camp software (version 4.6.2., Garmin Ltd.) for further analyzation. Processing tasks consisted of extracting the time labels, as well as the time (T, 5 s) and speed (S, km/h), for each of the collected locations as text strings. These were transferred to an MS Excel spreadsheet, where the time and speed were converted into numbers using simple MS Excel functions. The data collected by the accelerometer was downloaded using its dedicated software. Then it was exported as an MS Excel .CSV file containing the time labels and values of the acceleration (A, g) on three reference axes, as well as the vector sum of the three. Because of the different sampling rates that were set for the devices, a simple procedure was used to extract every fifth value from the acceleration data. The time labels were then used to pair the processed data from both devices.

Part of the data analysis such as characterizing the engine state and extracting the time consumption specific to distinguishable events was done in MS Excel. There are many systems that can be used to describe, characterize and categorize the inputs and outputs when studying the performance of agriculture- and forestry-related procurement systems (ASAE 2011; Lu and Ackerman 2012). This study used the IUFRO classification system (Björheden *et al*. 1995). In particular, the non-work and work time categories were the subject of this study, with the aim of separating the productive time from the non-work time. In the IUFRO classification system, productive time consists of the main and complementary work time categories. The main work time was assimilated in this study as the effective cutting time (CT, s), while the complementary work time (AT, s) was associated with other categories, such as walking with the brush cutter running without cutting within the plot and walking with the brush cutter stopped within the plot. All of the other categories were treated as non-work time (ST, s). The sum of all of the time categories was considered to be the total study time (TT, s). Because of the sampling strategy, this study assumed a time consumption data accuracy of ±5 s.

The first step was that of comparing the original acceleration data pool with the refined one to check for eventual data loss caused by resampling. The checking procedure consisted of extracting the engine running time data from both sets based on the acceleration behavior, followed by a percent comparison of the two. Then, to extract the time consumption data, a threshold setting procedure was used. First, the acceleration (A) data as vector sums was plotted against the speed (S) data extracted from the GPS files. Movement detection was based on a threshold set at a S greater than 0.5 km/h. The assumed threshold was documented based on the speeds reported in the previous study by Talagai *et al*. (2017), as well as on the figures reported by other studies related to GPS movement and speed change detection (Keskin and Say 2006; Eisenbies *et al*. 2014; Bush *et al*. 2015).

Two thresholds were set for the A data. The first one was set at 1.5 g to characterize the engine non-working state. The device used in this study captures accelerations close to 1 g when detecting no vibrations. The second threshold was set to 4 g to distinguish between the engine running (TR, s) and stopped (TS, s) times in which other events occurred that caused accelerations in the range 1.5 g to 4 g, such as replacing the steel blade. The thresholds set for the GPS and accelerometer data were further used to characterize specific events, including engine stopped and no movement ($A \leq 1.5$ g, $S \leq 0.5$ km/h) corresponding to ST, engine stopped and movement within the plot ($A \leq 1.5$ g, $S > 0.5$ km/h) corresponding to AT, engine stopped and movement outside the plot ($A \leq 1.5$ g, $S > 0.5$ km/h) corresponding to ST, and cutting events ($A \geq 4$ g, $S > 0.5$ km/h) corresponding to CT. To properly distinguish the events located outside the plot, this study also used the open-source software QGis (https://qgis.org/en/site/) to map the data. To this end, a .SHP layer was designed to store the original GPS data. It was then used to import and pair the data processed in MS Excel. The first analysis aimed to separate and map the two engine states (running and stopped) and it was performed using only the threshold set for acceleration. The second analysis aimed to distinguish between the time consumption categories and it supposed the use of a simple coding procedure in MS Excel V.B.A. to code the events as numbers and to extract the time consumption of each event. The obtained codes were imported to the .SHP file and plotted as a second map in QGis, while the time consumption data was used for further performance assessment. To evaluate the productivity and efficiency of the operations, estimates of the time consumption data (that were produced using the above described procedures) and characteristics of the plot (total row length and plot area) were used. The productivity was estimated as the ratio of operated area to time inputs, while the efficiency was estimated as the inverse ratio.

RESULTS AND DISCUSSION

This study covered more than 5400 GPS positions and almost 26700 acceleration samples. Figure 3 shows the differences between the two sampling approaches in terms of shares in the total study time (TT). Resampling the data led to similar results in terms of recognition accuracy for the two engine states (TS and TR), as the differences between the two were less than 0.01%.

Most of the time (> 75%), the engine was recognized to be in the running state, which could have indicated a high proportion of productive time (Figs. 4 and 5). Such a good recognition of the running time may help in designing further research on relating the fuel intake to the engine running time.

A detailed overview of the recognition accuracy of the original and resampled data is given in Fig. 4, which shows the engine running (TR) and stopped (TS) states based on the used threshold ($A = 4$ g). Preparing the brush cutter, including mounting and dismantling the sawing blades, were events that were characterized by very short durations where the acceleration exceeded 1.5 g, but it was less compared to that of the cutting activity. Also, the placement and takedown of the device on the brush cutter was characterized by an acceleration that exceeded 4 g without reaching the level specific to cutting activities.

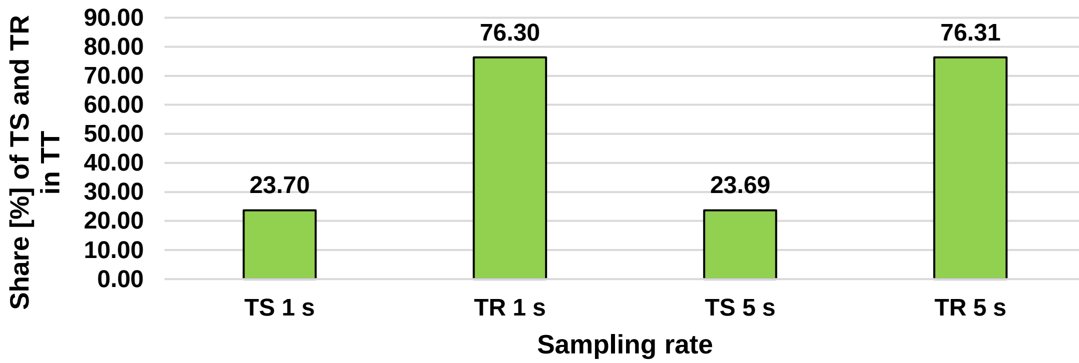

Fig. 3. Shares of the TS and TR states in the TT depending on the sample rate

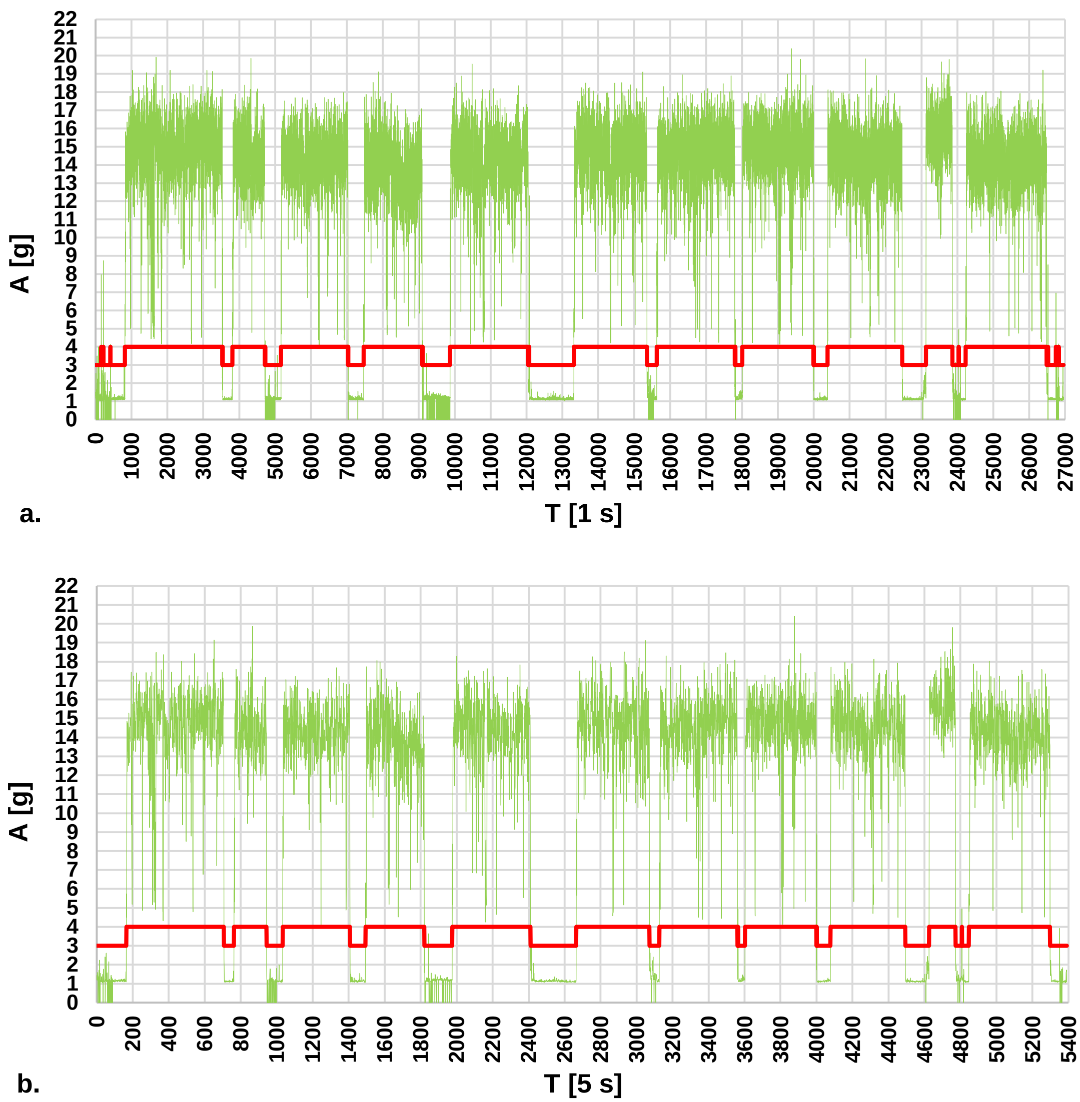

Fig. 4. Recognition accuracy of the TS and TR states during the TT for the 1-s (a) and 5-s (b) sampling rates; green - acceleration data pool; and red - state of the engine (running: A = 4 g, and stopped: A = 3 g)

This can be seen in Fig. 4a and occurred at the beginning and end of the work day. However, after data resampling, such events were removed from the data pool. While the approach used in this study succeeded in separating the two engine states, the field study also indicated the presence of delays, during which the engine was in the running state.

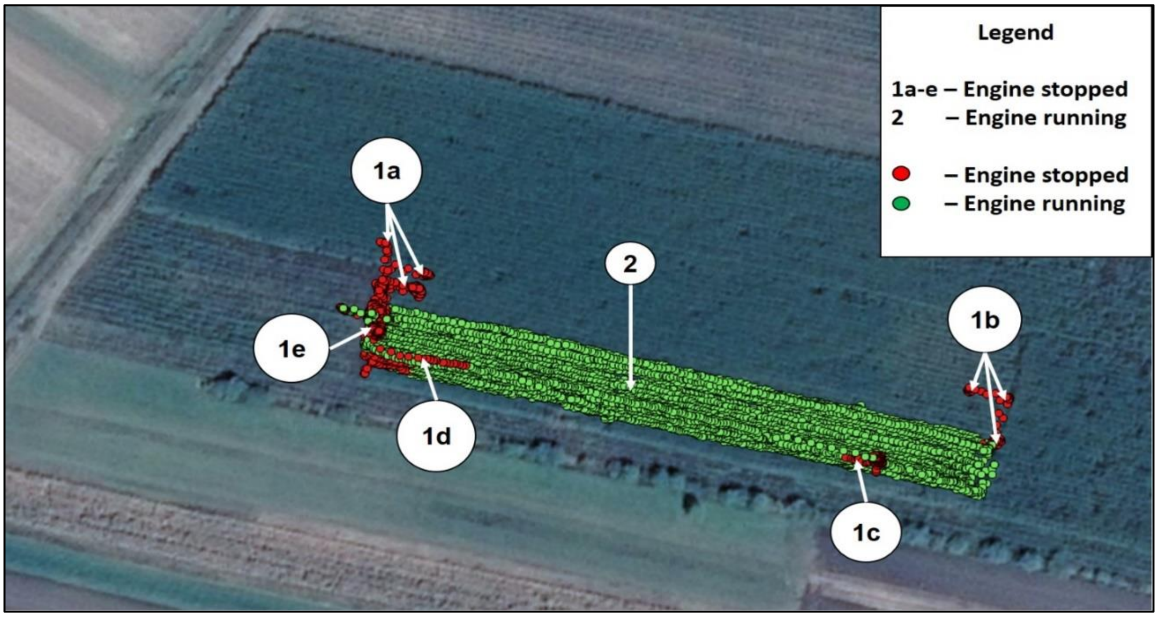

Fig. 5. Engine state plotted on the map; 1a - engine switched off during preparation of the brush cutter at the beginning of the study, including fueling, resting time as the felling progressed, and other events; 1b - rest time at the row ends and personal time; 1c - rest and fueling time in the field; 1d - moving with the engine stopped for repairing at the end of a row; 1e - rest and other events at the end of the crop; and 2 - engine running

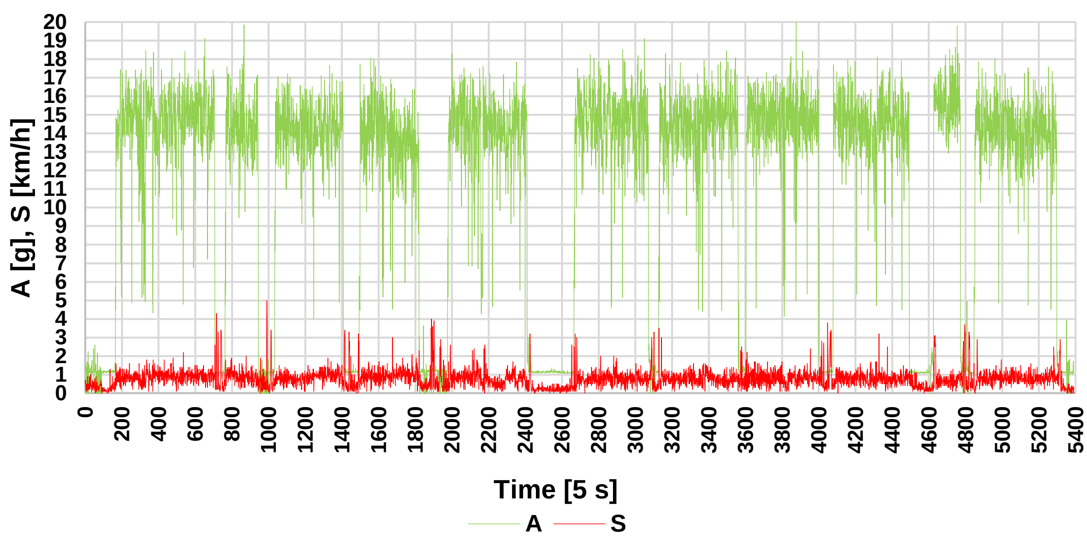

Fig. 6. Acceleration and movement speed behavior in the resampled data pool

Figure 6 shows the acceleration and speed behavior of the studied data plotted against the time. Specific events can be identified just by looking at the plotted data. In general, the cutting events were characterized by higher accelerations and smaller speeds.

Another type of event was illustrated in the center of the figure, where both the speed and acceleration dropped, which indicated ST. Other events that occurred were those where the speeds were greater than 2 km/h and the acceleration was very low, which indicated movement with the engine stopped.

The results of the time consumption separation of the categories are shown in Fig. 7. The CT accounted for almost 62% of the TT, regardless of the corrections made after visualizing the data plotted in QGis. Less than 1% of the TT was rated as AT. The ST, which included resting and meal time, personal time, and delays due to various reasons, accounted for more than 37% of the TT. Part of the AT (70 s) had to be shifted to the ST following the visualization of the data plotted in QGis. This corresponded to a walking event outside the field because of personal reasons. Altogether, the productive time accounted for approximately 62% of the TT, which was almost 7.5 h. This figure was close to the main work time, which indicated a good prediction of both categories by the studied time separation algorithms.

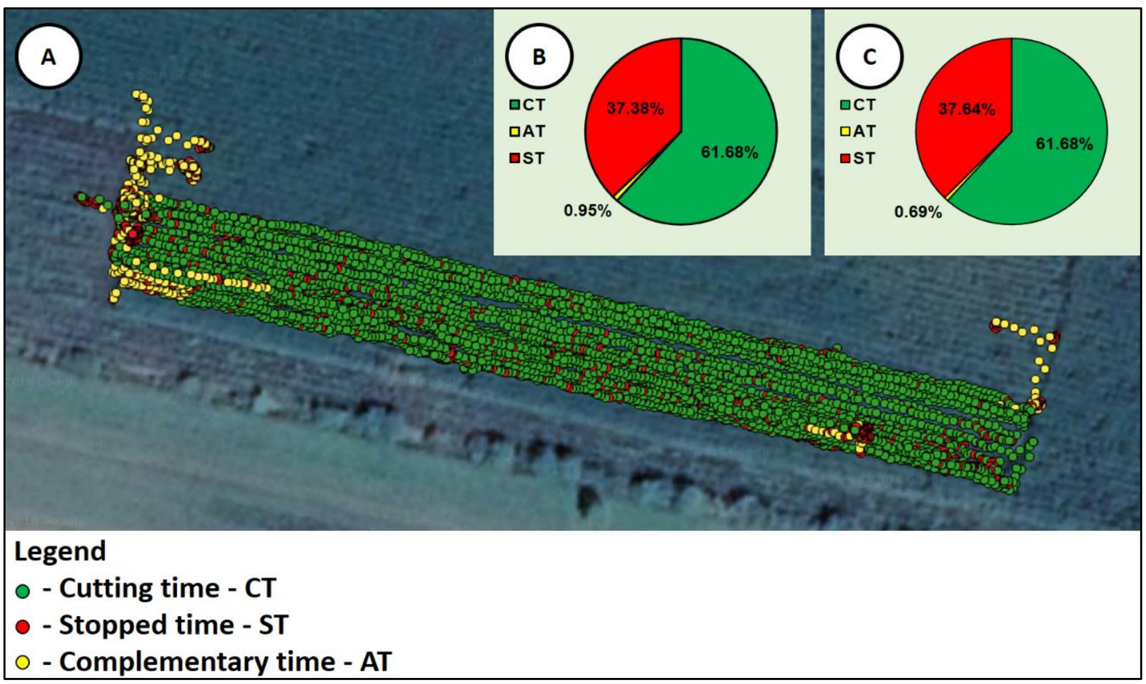

Fig. 7. Separation of the time consumption categories; A - general overview as yielded by the separation algorithm; B - shares of the time consumption predicted by the separation algorithm; and C - shares of the time consumption after data refining supported by visualization in QGis

During observation, the crew harvested 11 twin rows (mean length of 210 m), which accounted for a total row length of 4620 m, and an area of 0.5 ha, which resulted in a gross production rate of 0.07 ha/h and net production rate of 0.11 ha/h. This productivity was compared with the results reported by Talagai *et al*. (2017). While the expectations were to have an improved production rate because of the presence of smaller stems to be felled, the rates were actually much smaller compared with those reported by Talagai *et al*. (2017), who found gross and net production rates of 0.11 ha/h and 0.13 ha/h, respectively. Such differences may have been partly caused by time management being specific to their study, where the productive time accounted for almost 77% of the study time; the cutting speed in this study was about 1 km/h, which was remarkably greater compared with the cutting speed reported by Talagai *et al*. (2017). In their study, however, the operational and work organization conditions were different from those reported here. Consequently, the gross and net work efficiencies in this study were 14.98 h/ha and 9.34 h/ha, respectively. Such differences advocate for conducting long term studies that are able to manage the variations in the productive time during brush cutting operations, which are affected by many factors. For instance, Toupin *et al*. (2007) showed that in traditional forestry, the net efficiency of brush cutting operations may range between 5 h/ha and 35 h/ha, depending on various factors, including the vegetation cover, vegetation density, and presence of obstacles in the field. Additionally, motor-manual harvesting of willow SRCs deploys people in open fields during the late winter or early spring, which may further affect their operational performance because of the weather conditions.

Motor-manual harvesting operations of SRCs are generally characterized by lower productive performances, regardless of the tool used, with productivities of less than 0.3 ha/h (Burger 2010; Schweier and Becker 2012; Vanbeveren *et al*. 2015; Talagai *et al*. 2017). Also, the felling procedures are different in the case of brush cutters compared with those using chainsaws. The latter may require quite uncomfortable work postures during felling. Obviously, the factors mentioned above affect the productive performance in motor-manual harvesting of willow SRCs and they should be examined in detailed studies. The procedures described in this study could support the attempt of conducting long-term studies that manage the variation in operational conditions. Nevertheless, improvements to them may be further studied. For instance, in such operations, the rows may be seen as straight linear features. Therefore, by setting the borders of a given study area, followed by GPS data collection and processing, one could use the GPS bearing data to further distinguish and separate the events that may occur outside the bordered field. Such approaches have been used in traditional forestry (McDonald and Fulton 2005). A similar approach could be used to detect the length and location of turning events.

CONCLUSIONS

1. Thresholding the acceleration data to distinguish between the running (TR) and stopped (TS) engine states led to an accurate separation of the two states. This feature may help in evaluating the environmental performance of the studied operations by accounting for the direct fossil energy inputs.
2. Coupling GPS speed data with acceleration data, followed by threshold setting, allowed for a sufficiently accurate separation of the most important time consumption categories. This feature may support long term data collection to cope with variations in operational factors in such operations.
3. Even if aligned with existing results that indicate low productive performances in similar operations, the productive performance in the studied conditions was lower compared with a similar study. The main differences were in the general time management specific to this study and they advocate for further implementation of studies using the procedures described herein.

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