Productivity in partly mechanized planting operations of willow short rotation coppice

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Abstract. Biomass for energetic use can be procured from various sources including willow short rotation crops (WSRC). The feasibility of willow crops, however, is dependent on the costs incurred by operations such as the plantation, maintenance, harvesting and transport. In small scale applications, cost balancing often results in the use of equipment designed for general agricultural purposes to carry on the operational management of WSRC. This study evaluated the productive performance in planting operations of WSRC for a planting equipment consisting of regular farming tractors used to propel machines designed to support planting on single twin rows. Planting equipment consisting of 4 different types of farming tractors fitted with willow planting equipment was tested in 14 filed plots to be able to compute the main performance indicators such as the net and gross productivity rates. An evident variability in terms of time consumption on categories was observed at plot-level, and the planting time was related to a great extent to the operated area. The size of areas subjected to planting operations was the most important factor that affected productive performance. Variation of net productivity rate was explained largely by the ratio of the length of headland returning maneuvers to total length covered in a given plot. The model developed for the total study time shows that, in the observed conditions, it may take more than 7 hours to plant one hectare. The equipment taken into study stands for a flexible option for small-scale farmers which could increase the utilization rates of their farming tractors by using them in other agricultural operations when needed. In addition, the studied equipment fits well to very narrow and small-sized plots, as such situation is typical to Romania and other European countries.

Keywords: plantation, performance, biomass, mechanization, renewable energy

1. Introduction

Willow short rotation coppice (WSRC) is considered to be among the most successful fast-growing tree plantations that have a high potential in providing cleaner renewable energy and other raw materials [1-2]. It also contributes to climate change mitigation, by acting as carbon sink [3] and to the energy sufficiency and security [4-5]. Last, but not least, it holds an important role in the development of rural areas by the creation of new jobs [6-7] and by diversification of farm crops [1]. Among others, these are the main reasons that shape the current situation, in which WSRC are cultivated on increasingly extended areas in many parts of the world [1, 8], as well as for the increased interest in the science related to their biology [9], development and management [10], including the economic, environmental and operational performance of their establishment, maintenance, harvesting, transportation and conversion of their provided raw materials into bioenergy. Planting operations represent one of the most critical steps in the life cycle of WSRC because on their success depend other features of willow cultivation such as the yield and cost at the harvesting stage. In many countries, commercial-scale planting is carried-out by the use of highly-mechanized equipment [6, 11-13]. The fully mechanized approach enables an increased operational performance which contributes to cost reduction [12], therefore to an increased profitability. Still, the establishment costs are considered to be among the greatest contributors in the economy of WSRC [13], because the planting material and establishment can made up for more than 60% of such costs [12]. Most of the existing and currently used willow planting machines are designed to plant the cuttings vertically. They are characterized by different levels of mechanization and by a significant variability in the constructive concept, factors that, together with operational setups and planting layouts, are well known to affect the operational performance and should be taken into account in studies related to its estimation. Such studies should be based on large samples able to balance the effect of variability and to produce reliable statistics [15]. At the same time, performance of WSRC planting operations was less documented in the existing literature, judging at least by the type of machines used. In recent years, couple of studies have examined the planting performance to measure the influence of different factors on productivity, or to compare different methods in different countries and operational conditions. Some of them indicated planting rates in range of 0.27 to 1.22 ha h^{-1} for the Italian conditions [6] and of 0.89 to 1.14 ha h^{-1} for the North American conditions [11]. In particular, Manzone and Balsari [6] showed that the working rate of the planters is low independently by the planter type used, and species chosen. Bush et al. [11] identified several factors as areas of potential improvement: (i) improving planting stock and quality control, (ii) improving machine design for wet conditions and (iii) loading stems and clearing feeding systems at each turn. In addition, Lowthe-Thomas et al. [14] observed a planting performance of 0.25 ha h^{-1} that characterized the Welsh conditions of using step planters and Borz et al. [15] found productive performances of 0.149-0.230 ha h^{-1} following two experimental trials. Recently, Manzone et al. [7] tested a prototype for horizontal long cuttings planting in substitution of conventional short cuttings planted vertically (*Rotor*) finding a good performance in terms of field capacity, working quality, and fuel consumption but no difference was found between the two methods in terms of quality with good rooting results. Edelfeldt et al. [12] confirmed the effects of machine planting on sprouting and growth of shoots in soils with different degrees of compaction and the same authors [13] found that planting system had less effect on stool mortality, height development and biomass production. Therefore, one could expect quite a high variability given by the type of machine and planting setup and, based on the above, it can be observed that there are some limitations in data availability. In turn, this situation may affect the possibility to run other kind of scientific analyses that are essential for strategy and policy development [10], as well as for ensuring the sustainability of small-scale willow farming applications. For instance, data on productive performance enables comparisons between practices adopted in different geographical areas, contributing to a consistent reporting and development of related scientific disciplines by covering the regional variability [18]. It may also provide at least the data needed to estimate the financial effort and potential outcomes for those willing to invest in WSRC. This is even more so important, as in small-scale farming applications, both, the cultivated areas and the level of technology used are quite different compared to large scale, industrial applications. First of all, smaller agricultural holdings as well as their increased fragmentation and territorial dispersion are specific to most of the European countries [1]. Then, it is quite typical for the Eastern European countries to make use of partly-mechanized equipment given their shared socio-economic context in the past [19] and the developing period transited by them. Given the fact that willow cultivation is a relatively new economic field in Romania [20] and probably in other Eastern European countries, most of the operations are carried out using general-purpose equipment that is adapted to the operational needs [21-23]. It is the case of planting machines [17] which are simple aggregates propelled by tractors that make a substantial use of manual labor and for which work rates were not developed. Performance of human-made systems is crucial for their survival and it can be typically described by the use of a wide range of indicators [25]. Nevertheless, in many fields of science and practice, including that related to bioenergy procurement [6, 11, 22], performance is commonly evaluated in terms of time consumption, productivity rates and costs of given product systems. Such performance metrics are usually developed by time and motion studies and they have several important applications in the fields of economics and operational costing [26], ergonomics [24, 27-28], work design and improvement [29], energy inputs and energetic balance [30] and environmental footprint assessment [31-32], to name just a few; they are also the basic prerequisites for a deeper understanding of a system's behavior [33], system (re)engineering [34] aiming this way to the systems' optimization [32]. Therefore, in a broader sense, the availability of reliable production rates could be seen as one key factor in informing and building strategies and policies for a given field of operations or economic sector. To this end, the results of time and motion studies should be well-documented and accurate enough to be institutionally accepted [16] and they should cover the population variability [18]. Developing productivity rates, on the other hand, is a challenging work because it needs to include at least the variability given by the operational conditions, technology level and operators' skills and performance [16]. Often, this results in extensive field studies designed to cover and control the operational variability as well as in a significant effort in processing and analyzing the field collected data [36-37]. One way to balance the input resources needed to develop productivity rates is to automate as much as possible the activities related to field data collection and to the office processing and analysis [38]. The aim of this study was to document the productive performance of a partly mechanized willow planting system by the use of common performance metrics, enabling this way the development of willow planting rates. The objectives of the study were set in full compliance with the steps required to estimate the productive performance of equipment and systems used in short-rotation operations and they were designed to: (i) compute the main performance indicators of the studied system, produce planting rates and planting costs and (ii) find and analyze ways of improvement in terms of productivity increment.

2. Materials and Methods

2.1. Study sites

Planting operations were closely monitored in the central part of Romania (Fig. 1, Table 1), for a number of 14 plots that were considered representative for small-scale willow farming. In these plots, 14 field tests (hereafter *FT1* to *FT14*) were carried out by two similar planting aggregates, resulting in a number of 28 individual studies that aimed to cover the variability given by the plot size and capability of the used tractors. In addition, the workers used in operations were changed between certain field tests and were selected from an otherwise limited pool of professionals that had experience in such operations. *FT1* to *FT12* were carried on near Poian village (Covasna County) while *FT13* and *FT14* were carried out near Tărlungeni village (Braşov County). The total operated area which made the scope of this study accounted for 16.8 hectares (Table 1) and the plots were located on flat lands, in an altitudinal rage of 580 to 610 m a.s.l. In both counties, cultivation of willow (Salix spp.) to produce biomass is already well established and cultivars such as "*Inger*" and to less extent "*Tordis*" are used to plant small agricultural plots. Planting is done by the use of cheap, custom-made and locally-developed planting machines that are aligned to the operational management of willow cultivated in Romania. Such equipment is adapted to several types of crops and operations [15, 27]. A shared characteristic of the plots taken into study was that they were previously cultivated with regular agricultural crops such as potato, corn and other types of cereals. All the plots taken into study were characterized by the presence of well prepared (Fig. 2) fertile soils belonging to the chernozem soil class. Both areas of study are located in intramountainous depressions that are generally characterized by a moist temperate climate exhibiting a strong continentalism (Dfb according to Köppen classification) as well as by a colder weather compared to the surrounding regions.

Table 1. Location and summary description of field tests.

2.2. Planting Equipment and Work Organization

Two farming tractors fitted for planting operations were used and observed in each field test (Table 1, Fig. 2); to accommodate the potential variability given by the tractor type, this study tested four types of tractors commonly used to propel the planting equipment. The choice of tested tractors was based on their share in use and availability during the period of field tests. An 85.8 kW German-made Deutz 6.30 tractor and a 99.2 kW Finnish-made Valtra N123 tractor were used in *FT1-FT3* (Fig. 2), while in *FT4-FT12* the Valtra tractor has been replaced by a 60.4 kW Belarus 4.7L model. In *FT13* and *FT14* were used two Romanian-made tractors (Model UTB 450, 33.6 kW). For each field test and tractor used, the planting equipment (Fig. 2) consisted of a tracted wheel-drive steel-frame aggregate equipped with two furrow slicers mounted in the front part that were designed to create two parallel 0.75 cm-spaced slits in which the cuttings are manually pushed and closed by two packing wheels mounted at the rear part of the aggregate.

This equipment configuration enables planting of a single set of twin rows and covers a strip having a width of 2.25 m per pass. At the planting site, a two-stroke engine mechanical chainsaw (Husqvarna, 543 XP, 2.2 kW) was used to cut bunches of willow rods and to shape the cuttings needed for planting. These were manufactured from rods of "*Inger*" cultivar and had 18-20 cm in length and 1-2 cm in diameter. The resulting cuttings were stored in plastic boxes for planting. The preparation of the planting aggregate consisted of its mounting and connection to the three-point hitch of the tractor and placement on it of two boxes containing the cuttings at a height of cca. 60 cm above the ground. Then, two workers sat down on chairs placed on each side of the aggregate at a height of cca. 20 cm above the ground and communicated to the tractor driver to start the planting operation. For each tractor, a crew of 3 workers was used: 1 tractor driver and 2 manual planters. All of them had, at the study time, more than 4 years of experience in such operations and manual signals were used for coordination among the crew members. During the observation, there were few cases in which the area to be planted was not equally shared between the two tractors and planting crews, but such differences were minor in most of the situations. The effective planting was carried out, in tandem, by the two tractors operating in the same field, on successive planting strips (Fig. 2). At one of the headlands, which was opposite to that where the stock of cuttings was stored, maneuvers were undertaken to re-enter on new, adjacent strips. When reaching the headland where the stock of willow cuttings was stored, the two tractors performed exiting maneuvers as well as moving to the cutting stock for refilling, followed by re-entering on new planting strips.

2.3. Data Collection

Field observations were designed to collect data on time inputs and operational variables that were further used to estimate a set of metrics related to the planting performance (Table 2).

Time consumption structure used in this study was aligned to the general concepts of IUFRO [34] with some minor adaptations which were needed due to the specificity of observed operations. As such, the total study time (*TST*, in h) corresponded to the workplace time described by IUFRO classification, and it was further divided into: planting time (*PT*, in h) corresponding to the productive time, planting preparation time (*PPT*, in h) corresponding to supportive time, and delays (*DT*, in h) which corresponded to the work-related delay time according to the IUFRO classification. In order to get more detailed data, the planting time was divided further into main (*RT*, in h) and complementary time (*HRT*, in h) and the delay time was divided into row (*RD*, in h) and headland (*HD*, in h) delay time. *RT* category included the time spent in effective planting on the row, while *HRT* included the time spent in maneuvering at the headlands. Table 2 describes all the parameters collected, derived and analyzed in this study.

A commonly used technique to collect time and motion field data in many types of terrains is that of using Global Positioning System (GPS) receivers. While in open conditions the consumer-grade units are able to meet accuracies in range of 1 to 5 m [39-40], the usefulness of collected data itself depends on the complexity of studies and observed systems. Nevertheless, they can be successfully used to document movement and non-movement events, including speed, which are required to categorize most of the data needed in the development of productivity rates for less complex operational systems [17, 29]. To collect a part of the needed data, each tractor was equipped with a Garmin 60 STC GPS unit which was set to collect data at a sampling rate of 1 second (Fig. 2). Data collected by GPS units was complemented by field observations made by two researchers. The recorded files were saved for each plot and for each crew into a computer as GPX files, along with some supplementary observations. Excepting time consumption, the rest of variables and metrics used in this study were either derived or computed in the office phase of the study. In the field, however, a video camera was used to randomly collect the files needed in the evaluation of the number of planted cuttings. It was used to record data with the field of view oriented from the tractor's cab to the manual planters for a number of 21 planted rows that were randomly sampled across the study plots and which covered all the workers, standing for approximately 8% of the number of planted rows.

Table 2. Description of the concepts and variables used in the study.

2.4. Data Processing and Statistical Analysis

Field-collected GPS data was transferred and analyzed at the office using procedures that were similar to those described in Talagai et al. [29] and which were adapted to the requirements of this study. Fig. 3 gives an overview of the concept used to separate the time consumption categories at row and field test level, by the use of QGIS (https://www.qgis.org/en/site/) software. As shown, specific events such as effectively planting, row delays, headland maneuvers and delays were identified in the spatial architecture of the GPS-collected locations. For these events and similar to other studies [40-42], a methodological approach was adopted and the time consumption calculation was supported by Microsoft Excel (Microsoft, Redmond, U.S.A.) spreadsheets, based on the number of locations categorized as a specific event which were multiplied by the sampling rate. To do so, the database storing the locations collected for each field test was exported into Microsoft Excel files and, following this analysis, the results were summarized on field tests, crews and for all the study in the form of time spent in different events, extracted in seconds and then converted into hours. The operated area (*OA*, in ha) at row, field test and study level was computed using the row, total row (*RL*, in km) and study level length, based on the determination of row lengths carried on into QGIS software. The same procedure was used to compute the length of headland maneuvers at field test level (*HRL*, in km), based on the length determined in QGIS, extracted in meters and then transformed into kilometers.

Video files collected in the field were analyzed in detail to count the number of planted cuttings and to pair them to some operational parameters such as the row length and row time. This step was required to estimate the quantitative and qualitative performance of planting operations based on the number of planted cuttings. In particular, the ratios of headland maneuvers length to the row length and to the total length of a field test were calculated in order to describe the spatial quality. Since these ratios may affect the operational performance [15], their effect was further studied by regression modelling techniques. A similar procedure applied in an analogous study [17] was used to collect the data needed for localization and to characterize the time performance in order to detect what should be redesigned to improve the planting performance. These parameters are described in the section referring to the time share quality. As shown in Table 2, this study described the planting performance using metrics such as the speed (km h^{-1}), productivity (ha h^{-1}) and efficiency (h ha^{-1}) rates. As such, for the prediction of changes caused by different spatial layouts of the fields, and documentation of their effects on planting performance, this study distinguished between the overall planting speed, headland speed and the speed on the row. A similar approach was used to estimate the efficiency and productivity rates [17]. For these, a first approach aimed to reflect the field reality by computing the gross figures. Then, both, the net efficiency and productivity rates were calculated by excluding the delays and by including the planting preparatory time, giving this way an overview on how the planting operations would perform under conditions of a perfect work organization. However, this approach would be less realistic under real-world conditions. To show the effective differences between the crews and field plot conditions and to account for the variability induced by them, both, the effective and row-related efficiency and productivity rates were estimated in this study as well.

Statistical analysis was designed and implemented based on the general concepts described by Acuna et al. [16] which were adapted to derive the planting rates. In particular, the steps used herein consisted of normality check, computing the descriptive statistics and modelling using the least square linear regression technique. General descriptive statistics were used to characterize most of the parameters included in Table 2 while modelling techniques were used to estimate the functional relations between the time inputs and operational variables, as well as to show which of the spatial and time quality parameters and how do they affect the planting performance. All the tasks involving the transformation, computation and statistical analysis of the data were carried in Microsoft Excel. To extend its functionalities (*i.e.* normality checking), the Real Statistics add-in was installed and used in statistical analysis.

2.5. Economic Evaluations

To calculate the hourly cost of planting for different study sites, many parameters were considered [43] and the Miyata's method was applied [44]. The machine rate method described by Miyata includes fixed costs, variable costs, and labor costs (Table 3). The fixed costs (depreciation, interest, insurance, and taxes) were estimated using straight line depreciation [43]. The purchase prices and operator wages required for the cost calculations were obtained from catalogues and accounting records. The variable costs refer to those for fuel, lube, maintenance and repair, where the last two are calculated as a percent of depreciation. In the machine cost calculation, the relocation costs and the Value Added Tax (VAT) have not been considered. Fuel consumption was measured by evaluating the volume of fuel used to fill the fuel tank to the brim and recording the amount of fuel used during that day. Labor costs included hourly wages and overheads costs. Cost calculations were confirmed by the assumptions adopted in a recent economic study [45]. These parameters have been chosen to represent the reality of small-scale nonindustrial private farmers, which does not guarantee an intense annual utilization of mechanical equipment.

Table 3. Assumed cost parameters for machine rate calculation.

3. Results

3.1. Operational Variables and Time Consumption Estimates

The total operated area, as calculated in this study, amounted approximately 16.8 hectares, averaging about 1.20 hectares per study plot and circa 0.6 hectares per field test. There was, however, a significant variation in terms of operated area both, for the study plots and field tests (Table 4). For the later, the operated area varied between 0.106 and 1.561 hectares. The total row length averaged 2.67 km (median value of 2.23 km, Table 4) per field test while the total covered distance amounted, in average, approximately 3 km (median value of 2.5 km, Table 4) per field test. While in the studied conditions the headland returning maneuvers averaged only 0.27 km (median value of 0.2 km, Table 4), worth mentioning here that such maneuvers accounted at the study level for almost 7.5 km, standing for about 9% of the total covered distance which was of approximately 82 km (Table 4). Therefore, most of the covered distance was that specific to the on-row planting (91%, 74.7 km).

Field observations covered close to 118 hours (Table 4) out of which predominant was the time spent in planting operations which amounted more than 88 hours (75.6%). More than 73% of the planting time was spent in actually planting while the rest was spent in headland maneuvers. Delays represented a significant part of the total study time, accounting for almost 23 hours (19.4%). In the delay time category, more than 76% was specific to headland events belonging to the time consumption categories explained in Table 2. Preparatory time accounted for 5.8 hours (4.9%) of the total study time. On average, the total study time at field test level amounted approximately 4.2 hours (median value of 3.2 hours), with quite a large variation which was related to the size of the field tests. In the total study time, planting time was dominant accounting, on average, for approximately 3.2 hours (median of 2.6 hours); the row time consumption was, on average, 2.4 hours (median value of 2.0 hours) but it also varied widely in between less than 0.4 and almost 6 hours. Delays averaged almost one hour per field test (median value of 0.5 hours).

A detailed breakdown on time categories is given in Fig. 4 for each field test and crew showing an evident heterogeneity which was related mainly to the size of planted plots. Both, headland and row delays tended to increase in relative value as a function of the field size, which was not specific to planting preparation time. A similar behavior was observed in the case of row and headland time, which were proportional, in their increment, to the field plot sizes shown in Table 1. In case of *HT*, this effect was mostly related with the distance covered to reach the cutting supply stock at the headlands. Also, resupplying cuttings at the headland contributed to this situation, but a differentiation between this activity and other kinds of delays was not possible by the approach of this study. This was also specific to row delays which included along with other tasks, changing the empty cutting boxes with filled ones. However, such events were minor and probably contributed less to delays.

The most significant and useful factor, explaining the variation of time consumption, was the operated area (*OA*, in ha). Fig. 5 shows the dependence relation between most of the studied time consumption categories and the variation in size of the operated area. All of the developed models were highly significant ($\alpha=0.05$, $p<0.01$), and most of them succeeded to explain the variability of time consumption in proportions higher than 95% ($R^2>0.95$). The model developed for the total study time shows that, in the observed conditions, it may take more than 7 hours to plant one hectare. This outcome was supported by the statements of the equipment owner as he indicated that his typical planting rate is of one hectare per day. However, by excluding the delays, this figure will decrease to 77% of the original one (cca. 5.5 hours); under the assumption of no preparatory time which could be specific to plots located nearby, this would be further reduced to about 74% of the original figure. The magnitude of time spent on-the-row to effectively plant was affected to the greatest extent by the size of operated area (lowest intercept value), resulting in about 3.9 hours to plant one hectare. The variation in size of operated area explained the difference of time spent in headland maneuvers in a proportion of about 78%. This was the effect of the types of maneuvers undertaken at one of the headlands, were the planting equipment was driven, at each exit, forth and back from the cutting stock in order to resupply the crew with new boxes. Obviously, the magnitude of such maneuvers depended also on the plot's width therefore on the number of planted rows.

Table 4. Description of operational variables and time inputs.

3.2. Spatial Quality, Time Quality and Planting Performance Metrics

Table 5 gives an overview on the main performance metrics as they were estimated from the field-collected data. Planting speed averaged approximately 0.94 km h^{-1} and it varied between approximately 0.8 and 1.2 km h^{-1}, being affected to a great extent by some very slow maneuvers undertaken at the headlands. Here, the movement speed ranged in between less than 0.2 to more than 1.9 km h^{-1}, with a median value of approximately 0.3 km h^{-1}. The effective planting operations were, however, faster 1.17 km h^{-1}).

In the observed conditions (Table 5) the gross efficiency rate ranged, in the field tests, from about 5.5 to more than 10.5 h ha^{-1}, averaging about 6.7 h ha^{-1}. An obvious drop was found in the case of effective efficiency rate which averaged about 5.1 h×ha^{-1} while the on-row efficiency rate averaged cca. 3.8 h ha^{-1}. In these conditions, the gross productivity rate varied between approximately 0.10 and 0.18 ha h^{-1}, averaging, at the study level, approximately 0.15 ha h^{-1}. Different kind of delays affected the productivity rate as much as by almost 20%, since the net figure averaged approximately 0.18 ha h^{-1}. As shown, in Table 5, in the case of effective planting, the figure did not improve to a significant extent.

Fig. 6 shows the dependence relation between the variability of net productivity rate and the ratios' variability of headland length to total length and headland time to planting time respectively. Both parameters varied quite widely, with the first one in range of 0.03 to 0.29 and the second one in the range of 0.03 to 0.50 (Table 5). The developed models indicate an evident and proportional decrement of the production rate in relation to the mentioned ratios (Fig. 4). The dependence between the two was even more evident when using the time ratios (R^2 = 0.64), indicating that in order to increase the performance of planting operations one should redesign the time spent in headland movement events. As those events are related to the distance covered, probably a good approach to redesign the work organization would be to enable the mobility of the cutting resupplying stock as the work progresses in a given plot which would lead to a partial elimination of the headland maneuvers. To support this, a good overview of the analyzed ratio effects on the production rates could be provided just by looking at the extreme values [12-17-22]. When the ratio of *HL* to *TL* was of about 0.05 the increment in terms of production rate were almost 1.50 times compared to a 0.3 ratio, gaining this way an increment of about 50% in terms of production rate, which could contribute to the sustainability of small-scale willow planting applications. Similar results may be obtained when analyzing the time ratio.

3.3. Planting Cost

For each field test and tractor used, the hourly cost was calculated by assuming both, the gross and net efficiency rates. The difference found as the minimum and maximum cost of planting operations was due to the different hourly costs of the tractors used, as well as due to the variation in productive performance. The maximum values calculated were €304.80 ha^{-1} at site *FT1* and €289.41 ha^{-1} at site *FT3* where a Valtra N123 tractor was used, but these values were reduced when considering only the productive time (€244.17 ha^{-1} and €240.54 ha^{-1}, respectively). Costs per unit of product (€ ha^{-1}) were lower in sites where the planting operations were performed using UTB 450 and Belarus 4.7L tractors, thanks to the lowest hourly costs and to a better productivity. On average, the costs of these operations varied from €186.79 ha^{-1} (*FT9-12*) to €163.13 ha^{-1} (*FT13-14*) and, by considering only the productive time, the planting costs were estimated at €157.09 ha^{-1} and €129.76 ha^{-1}, respectively. Delay time increased the operating cost by 12–19% and planting costs increased as the proportion of the headland delay time increased.

Table 5. Descriptive Statistics of Spatial Quality, Time Quality and Planting Performance Metrics.

4. Discussion

The main aim of this study was to document the productive performance of partly-mechanized willow planting operations. As such, the study produced results that can be compared to those provided by the international literature enabling, at the same time, the attempt for improvement. In the international studies, for instance, operational speed was found to vary quite widely depending on the machine used and, probably, on the operational layout. Manzone and Balsari [6] have found speeds in the range of 1.0-1.2 km h^{-1} for a set of planting machines tested on prepared sandy soils and for planting densities of 6,700 individuals per hectare. Machines from other classes, such as the Salix Maskiner step planters, were found to be able to sustain higher operational speeds that are in the range of 2 to 5 km h^{-1} [6, 11]. Operational speed as derived from our field tests was in range of 1.0 to 1.3 km h^{-1} and it was comparable to that of similar equipment (Allasia) described by Manzone and Balsari [6]. However, the variation of operational speed was low, as shown by this study, and further increments in this parameter are less likely to occur if the use of the described level of technology and planting density is in question. This is because one cannot expect the workers to be able to keep the pace in manual planting work at higher speeds for the same planting density. On the other hand, an improvement may rest in redesigning the planting equipment to be able to plant, at the same speed and planting density, a set of twin rows per pass, an attempt whose success will ultimately depend on the tractor capabilities and the technical limitations imposed by the shape and size of plots to be planted. As a fact, the equipment owner has developed such a planting machine but still, it is currently used to a less extent due to a limited size of plots to be planted.

In terms of general economic performance, a change in the system used to place the regeneration material (lay flat) into the soil was found to substantially contribute to cost reduction [13]. Still, the outcomes of this approach in terms of sprouting viability and survival rates need to be tested in various climate conditions to be able to infer its effectiveness for other regions and, in case of success, it will require a significant change in the concept of machines used. At the same time, a higher degree of mechanization, that usually comes with increasingly specialized machines, needs a high initial investment that is often inaccessible to small scale farmers. This is a commonly known issue for those machines that are produced in a limited series. These reasons, as well as the economic improvement that can be achieved in terms of survival rate

by manual insertion of cuttings into the soil [12] still make the tested planting option a viable alternative for small scale farmers who need flexible machines to cover the operational needs of various types of crops. In this context, the productivity and efficiency rates found in this study indicate a productive performance that was lower compared to the results reported by others. In essence, this may be attributed to the planting scheme which was quite dense in this study, a situation that has consequences in the planting speed, therefore in the productivity and efficiency rates. For less individuals planted per hectare and for a similar level of technology, Manzone and Balsari [6] found productivity rates in range on 0.28 - 0.57 ha h^{-1}. The differences between their results and the results of this study (0.18 ha h^{-1}) may rest, therefore, in the planting density; obviously, other types of machines may reach productivity rates of more than 1 ha h^{-1} [6, 11] and these high differences may be explained by both, the technology used and the planting density. Results similar to those reported herein were found in small trials carried out in Romania using the same level of technology [17] validating, to some extent, the planting rates developed by this study.
In terms of efficiency and productivity improvement, a special care should be given to the organizational side of the operations. Similar to many other studies on the operational performance of various kind of equipment, finding ways to exclude the delays has a great potential in the attempt to improve the productive performance. On the other hand, reality is that delays appear to exhibit a random occurrence and operational factors may contribute less to their frequency and duration. For this reason, a better organization of work and its logistics can substantially improve the status quo. In this regard, headland delays may contribute by up to 20% in the workplace time [9] a fact that has been found also in this study that showed a proportion of 25 to 75% of the delays found on the row and at the headland, as well as a proportion of 19.5% of delay time in the workplace time.
The size of areas subjected to planting operations was the most important factor that affected productive performance. Apart from a relatively constant operational speed, the size of operated plots shaped a specific distribution of the time spent in maneuvers at the headlands. Productive performance may be related to work organization also in terms of number of machines used in a given plot. To this end, Borz et al. [17] have found net productivity rates in planting operations which were of 0.22 and 0.30 ha h^{-1} respectively, being higher than those estimated by this study (0.18 ha h^{-1}). In their study, however, the organization of work consisted of using a single machine in a given plot. For this reason, one could assume that operation by two tractors may increase the ratio of delays due to the need of a machine to wait at the headlands for the second machine to exit before entering to a new strip. Nevertheless, operating a given area by two machines contributes to a significant reduction in time consumption, therefore the overall productivity rate is expected to increase.

5. Conclusion

To assess the productive performance of a partly mechanized willow planting system, 28 field experiments were performed in the central part of Romania. The results demonstrated that the productive performance of planting is influenced by the size of areas subjected to such operations. To achieve an improved performance, one should (re)engineer the ratio of headland length to total or row length a fact that can be achieved by a redesigning the organization of work, especially by enabling the mobility of planting material stock. Such an attempt will contribute to a redistribution of time spent in headland maneuvers and row operation which, in turn, will increase the productivity and, most probably, will decrease the operation costs. The equipment taken into study stands for a flexible option for small-scale farmers which could increase the utilization rates of their farming tractors by using them in other agricultural operations when needed. The results of this study can be used to set the piece rate, in the rationalization of work, in work scheduling, and in cost estimation. In fact, the model developed by this paper may be useful in production organization when dealing with similar work conditions. In addition, the studied equipment fits well to very narrow and small-sized plots, as such situation is typical to Romania and other European countries.
The merit of this study is that it builds up on a reasonably wide dataset collected in the field (over 16 hectares monitored) and, therefore, it accounts for operational variability, contributing by a more informed approach in describing the operational performance, showing the pathways that could be used for the

improvement of operations. Furthermore, ergonomic factors should be evaluated to perform a global operative monitoring because investing in occupational safety and health could provide improved productivity and working conditions [46-47].

Considering the worldwide diffusion of small farms dedicated to energy crops cultivation as well as the economic barriers due to expensive specialized equipment, this study brings evidence on the performance of a partly mechanized planting system that could be a viable alternative for small-scale willow farming.

Acknowledgements

Some activities in this study were funded by the inter-institutional agreement between Transylvania University of Braşov (Romania) and Mediterranean University of Reggio Calabria (Italy).

The authors acknowledge the technical support of the Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov in designing and conducting this study. The authors would like to thank the management of Transilvania University of Brasov for providing the funds needed for purchasing the dataloggers used in this study. Also, the authors would like to thank the owner of planting equipment - Mr. Eng. Arpad Domokos - for agreeing to carry on the study in his operations and for the logistical support provided during the field phase of the study. This paper reports partial results of the PhD thesis under development by Eng. Nicolae Talagai - Evaluation of productive performance in partly mechanized planting and harvesting operations of willow short rotation coppice, under the coordination of PhD School of the Transilvania University of Brasov.

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Table 1

Table 1. Location and summary description of field tests.

Study Location (Field Test Area)	Abbreviation	Operated Area [ha]	Observation Date	Tractors used	Geographic Location
FT1 (1.940)	*FT1_1* *FT1_2*	1.087 0.853	26/04/2017	Deutz 6.30 Valtra N123	N 46° 03' 43'' E 26° 11' 29''
FT2 (0.212)	*FT2_1* *FT2_2*	0.106 0.106	26/04/2017		N 46° 04' 01'' E 26° 11' 38''
FT3 (1.486)	*FT3_1* *FT3_2*	0.743 0.743	26/04/2017		N 46° 03' 50'' E 26° 11' 10''
FT4 (1.022)	*FT4_1* *FT4_2*	0.533 0.489	27/04/2017	Deutz 6.30 Belarus 4.7L	N 46° 03' 51'' E 26° 11' 11''
FT5 (0.681)	*FT5_1* *FT5_2*	0.324 0.357	28/04/2017		N 46° 03' 52'' E 26° 10' 07''
FT6 (1.119)	*FT6_1* *FT6_2*	0.652 0.467	28/04/2017		N 46° 02' 15'' E 26° 10' 30''
FT7 (1.351)	*FT7_1* *FT7_2*	0.600 0.751	28/04/2017		N 46° 02' 41'' E 26° 11' 50''
FT8 (1.165)	*FT8_1* *FT8_2*	0.665 0.500	28/04/2017		N 46° 03' 02'' E 26° 11' 12''
FT9 (0.420)	*FT9_1* *FT9_2*	0.218 0.202	29/04/2017		N 46° 03' 33'' E 26° 10' 20''
FT10 (0.578)	*FT10_1* *FT10_2*	0.289 0.289	29/04/2017		N 46° 03' 28'' E 26° 10' 12''
FT11 (2.489)	*FT11_1* *FT11_2*	1.119 1.370	29/04/2017		N 46° 03' 03'' E 26° 11' 53''
FT12 (0.457)	*FT12_1* *FT12_2*	0.304 0.153	29/04/2017		N 46° 03' 08'' E 26° 12' 06''
FT13 (0.923)	*FT13_1* *FT13_2*	0.502 0.421	24/03/2017	UTB 450	N 45° 40' 34'' E 25° 45' 38''
FT14 (2.973)	*FT14_1* *FT14_2*	1.561 1.412	24/03/2017		N 45° 40' 07'' E 25° 45' 41''
TOTAL	**28**	**16.816**	-	-	-

Table 3

Table 3. Assumed cost parameters for machine rate calculation.

Parameter	Valtra N123	Deutz 6.30	Belarus 4.7L	UTB 450
Purchase price (€)	53,000	42,000	32,000	24,000
Salvage value (€)	10,600	8,400	6,400	4,800
Estimated life (n year)	10	10	10	10
Annual depreciation (€*year^{-1})	4,240	3,360	2,560	1,920
Interest (€* year^{-1})	1,696	1,344	1,024	768
Taxes and insurance (€* year^{-1})	2,714	2,150	1,638	1,229
Total fixed cost (€* h^{-1})	8.83	6.99	5.33	4.00
Fuel & Lubricant (€* h^{-1})	18.41	17.05	14.61	12.28
Total labour cost (€* day)	21	21	21	21
Repair & maintenance (€* h^{-1})	3.03	2.40	1.83	1.37
Total variable cost (€* h^{-1})	24.44	22.45	19.44	16.65
Total hourly cost (€* h^{-1})	33.27	29.44	24.77	20.65

Table 4

Table 4. Description of operational variables and time inputs.

Variable	Descriptive statistics[a]				
	Minimum	Maximum	Median	Sum	Share
Operational variables					
Operated Area - *OA* (ha)	0.106	1.561	0.501	16.816	-
Row Length - *RL* (km)	0.471	6.937	2.227	74.747	90.9
Headland Returning Length - *HRL* (km)	0.034	0.939	0.200	7.438	9.1
Total Length - *TL* (km)	0.516	7.876	2.504	82.185	100.0
Time inputs					
Row Time - *RT* (h)	0.416	5.869	1.982	65.861	74.1[b]
Headland Time - *HT* (h)	0.081	2.933	0.529	22.971	25.9[b]
Planting Time - *PT* (h)	0.531	8.455	2.577	88.832	75.6[d]
Planting Preparation Time - *PPT* (h)	0.000	1.043	0.143	5.812	4.9[d]
Row Delay Time - *RD* (h)	0.000	0.610	0.153	5.381	23.4[c]
Headland Delay Time - *HD* (h)	0.057	2.285	0.378	17.577	76.6[c]
Delay Time - *DT* (h)	0.132	2.844	0.503	22.958	19.5[d]
Total Study Time - *TST* (h)	0.726	10.984	3.213	117.601	100.0

Note: [a]Most of the data failed the normality check test, therefore median values were used for reporting, [b]Shares in the planting time, [c]Shares in the delay time, [d]Shares in the total study time.

Table 2

Table 2. Description of the concepts and variables used in the study.

Parameter	Abbreviation (unit)	Description
Operational variables		
Operated Area	*OA* (ha)	Total (planted) area covered by a crew in a given *FT*
Row Length	*RL* (km)	Total row length (distance) planted (covered) by a crew in a given *FT*
Headland Returning Length	*HRL* (km)	Total distance (length) covered by a crew in moving maneuvers at the headlands in a given *FT*
Total Length	*TL* (km)	Sum of *RL* and *HRL* for a given crew and *FT*
Time inputs		
Row Time	*RT* (h)	Time spent by a crew in moving on the rows and effectively planting in a given *FT*
Headland Time	*HT* (h)	Time spent by a crew in moving at headlands in a given *FT*
Planting Time	*PT* (h)	Sum of *RT* and *HT* for a given *FT* and crew
Planting Preparation Time	*PPT* (h)	Time spent by a crew at headland to make preparations in a given *FT*
Row Delay Time	*RD* (h)	Time spent by a crew when stopped on the row in a given *FT*
Headland Delay Time	*HD* (h)	Time spent by a crew when stopped at headlands in a given *FT*
Delay Time	*DT* (h)	Sum of *RD* and *HD* for a given *FT* and crew
Total Study Time	*TST* (h)	Sum of *PT*, *PPT* and *DT* for a given *FT* and crew
Performance metrics		
Spatial Quality		
Ratio of *HRL* to *RL*	*R_HRL-RL*	Ratio of the headland returning length to the row length
Ratio of *HRL* to *TL*	*R_HRL-TL*	Ratio of the headland returning length to the total covered length
Ratio of *RL* to *TL*	*R_RL-TL*	Ratio of the row length to the total covered length
Time Share Quality		
Ratio of *HT* to *RT*	*R_HT-RT*	Ratio of the headland returning time to the row time
Ratio of *HT* to *PT*	*R_HT-PT*	Ratio of the headland returning time to the planting time
Ratio of *RT* to *PT*	*R_RT-PT*	Ratio of the row time to the planting time
Operational Speed		
Speed on the Row	*RS* (km h^{-1})	Average speed of the tractor when moving on row in a given *FT*
Speed at the Headland	*HS* (km h^{-1})	Average speed of the tractor when moving at the headlands in a given *FT*
Speed during Planting	*PS* (km h^{-1})	Average speed of a tractor when moving in a given *FT*
Planted Cuttings		
# of Cuttings per Hour	*CT* (c h^{-1})	Based on a number of 21 sampled rows and calculated as the ratio of the number of cuttings to the planting time (*PT*)
# of Cuttings per Meter	*CM* (c m^{-1})	Based on a number of 21 sampled rows and calculated as the ratio of the number of cuttings to the row length
Distance between Cuttings	*DC* (m)	Based on a number of 21 sampled rows and calculated as the ratio of the row length to the number of planted cuttings
Planting Rates		
Gross Productivity Rate	*GPR* (ha h^{-1})	Productivity rate calculated based on *TST*
Net Productivity Rate	*NPR* (ha h^{-1})	Productivity rate calculated by excluding *DT*
Effective Productivity Rate	*EPR* (ha h^{-1})	Productivity rate calculated based on *PT*
On-Row Productivity Rate	*RPR* (ha h^{-1})	Productivity rate calculated based on *RT*
Gross Efficiency Rate	*GER* (h ha^{-1})	Efficiency rate calculated based on *TST*
Net Efficiency Rate	*NER* (h ha^{-1})	Efficiency rate calculated by excluding *DT*
Effective Efficiency Rate	*EER* (h ha^{-1})	Efficiency rate calculated based on *PT*
On-Row Efficiency Rate	*RER* (h ha^{-1})	Efficiency rate calculated based on *RT*

Table 5

Table 5. Descriptive Statistics of Spatial Quality, Time Quality and Planting Performance Metrics.

Variable	**Descriptive statistics**		
	Minimum	Maximum	Median
Performance metrics			
Spatial Quality			
Ratio of *HRL* to *RL* - *R_HRL-RL*	0.03	0.41	0.08
Ratio of *HRL* to *TL* - *R_HRL-TL*	0.03	0.29	0.08
Ratio of *RL* to *TL* - *R_RL-TL*	0.71	0.97	0.92
Time Share Quality			
Ratio of *HT* to *RT* - *R_HT-RT*	0.03	0.98	0.30
Ratio of *HT* to *PT* - *R_HT-PT*	0.03	0.50	0.23
Ratio of *RT* to *PT* - *R_RT-PT*	0.50	0.97	0.77
Operational Speed			
Speed on the Row - *RS* (km h^{-1})	1.00	1.27	1.17
Speed at the Headland - *HS* (km h^{-1})	0.14	1.97	0.31
Speed during Planting - *PS* (km h^{-1})	0.81	1.22	0.94
Planted Cuttings			
# of Cuttings per Hour - *CT* (c h^{-1})	4515.4	6089.8	5032.0
# of Cuttings per Meter - *CM* (c m^{-1})	1.81	2.59	2.32
Distance Between Cuttings - *DC* (m)	0.39	0.55	0.43
Planting Rates			
Gross Productivity Rate - *GPR* (ha h^{-1})	0.094	0.179	0.149
Net Productivity Rate - *NPR* (ha h^{-1})	0.123	0.218	0.182
Effective Productivity Rate - *EPR* (ha h^{-1})	0.135	0.223	0.196
On-Row Productivity Rate - *RPR* (ha h^{-1})	0.225	0.285	0.263
Gross Efficiency Rate - *GER* (h ha^{-1})	5.589	10.627	6.696
Net Efficiency Rate - *NER* (h ha^{-1})	4.577	8.113	5.497
Effective Efficiency Rate - *EER* (h ha^{-1})	4.484	7.400	5.114
On-Row Efficiency Rate - *RER* (h ha^{-1})	3.508	4.438	3.797

Fig. 1. Location of sites chosen for the field tests.

Fig. 2. Description of equipment used and work organization: a - general description of the planting equipment (field tests in Poian, Covasna): 1 - plastic box for cutting storage during planting; 2 - weight balancing system; 3 - steel wheels for slit cover, 4 - wheel drive of the aggregate, 5 - strip delimitation device; b - placement of the GPS receiver (field tests in Tărlungeni, Brasov), c - planting organization (field tests in Poian, Covasna).

Fig. 3. The concept used in separation of time consumption categories: left - a part of the mapped locations; right - detailed view on GPS collected data: 2 - on-row delays, 3 - headland delays; 4 - headland maneuvers.

Fig. 4. Time distribution on the studied categories and field tests.

Fig. 5. Prediction models showing the variation of time consumption data explained by the variation of operated area. Legend: TST - total study time, PT* - planting time including planting preparation time, PT - planting time, RT - row time, HT - headland time, OA - operated area.

Fig. 6. Dependence relation between the net productivity rates and ratios *HRL-TL* (a) and *HT-PT* (b).

Figure 1

Click here to access/download;Figure;Fig 1.tif

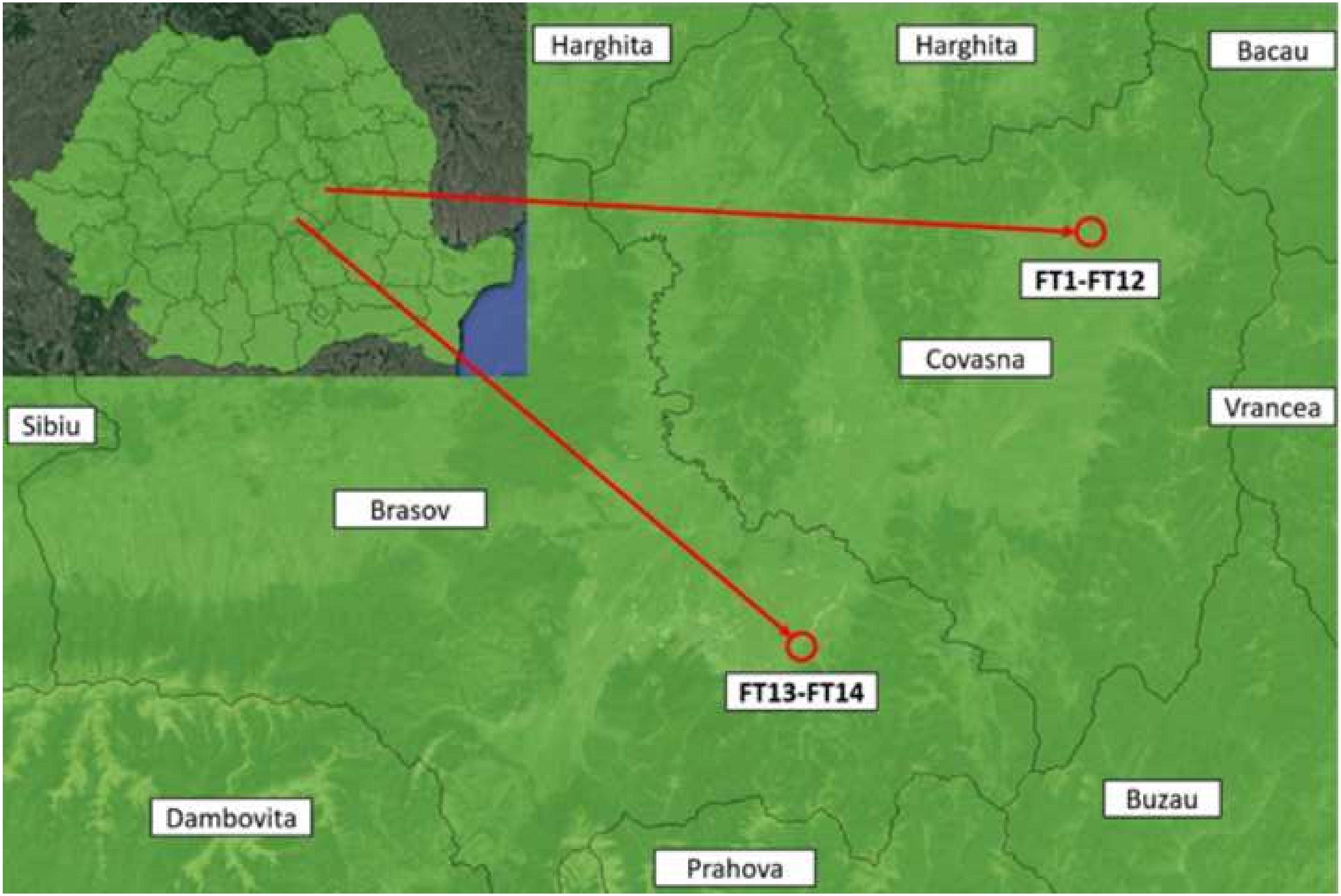


Figure 2

Click here to access/download;Figure;Fig 2.tif

Figure 3

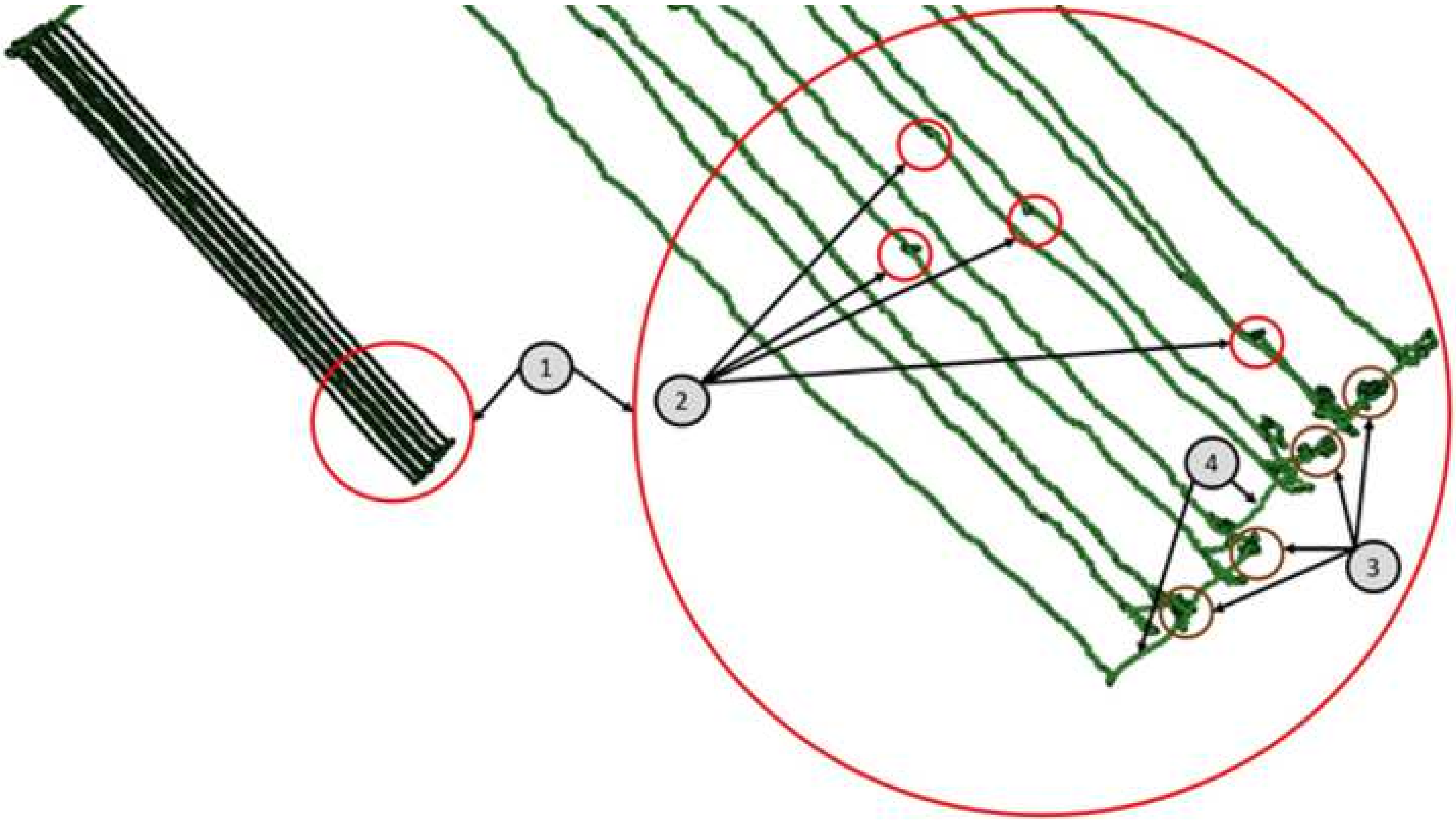


Figure 4

Click here to access/download;Figure;Fig 4.tif

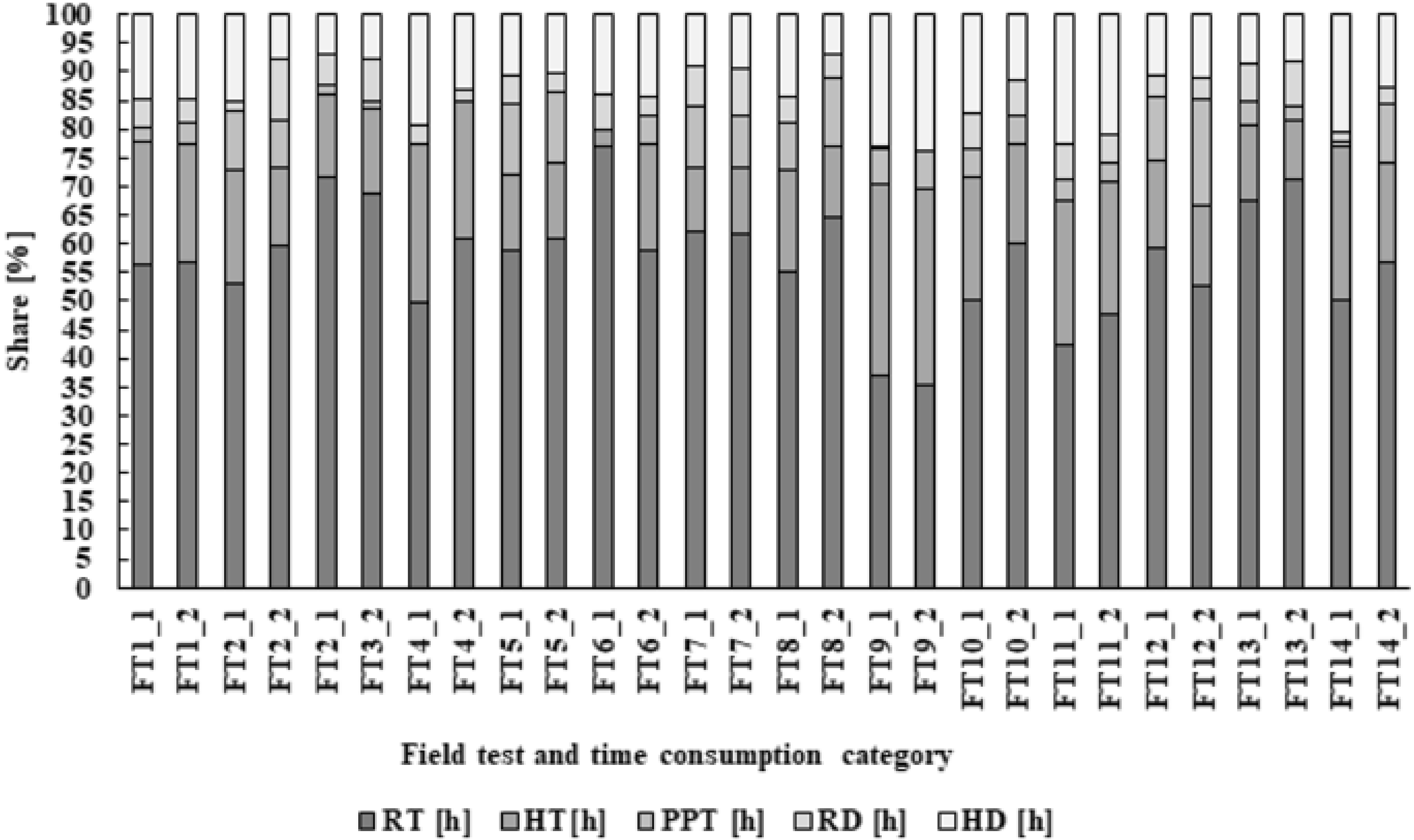
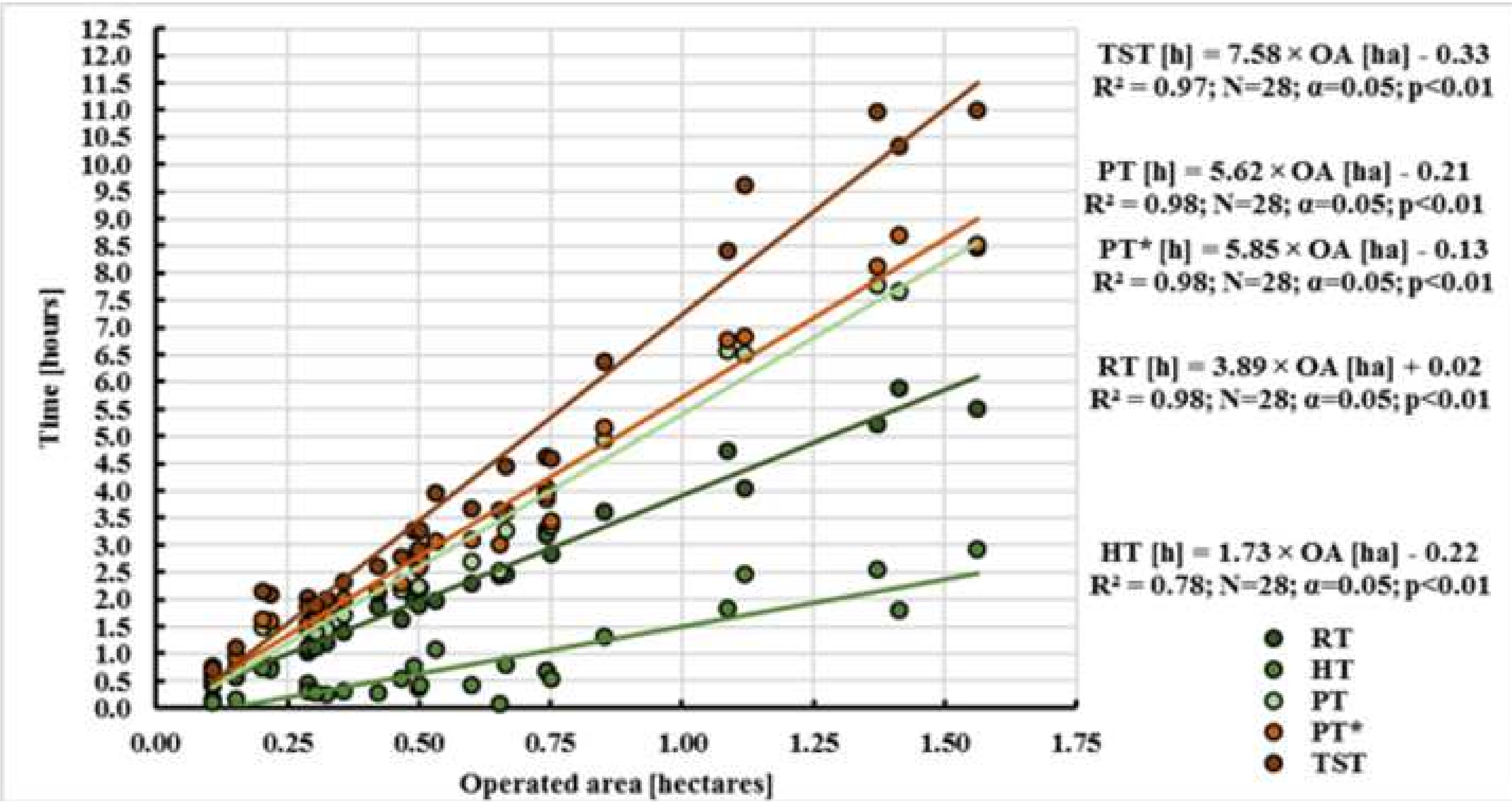
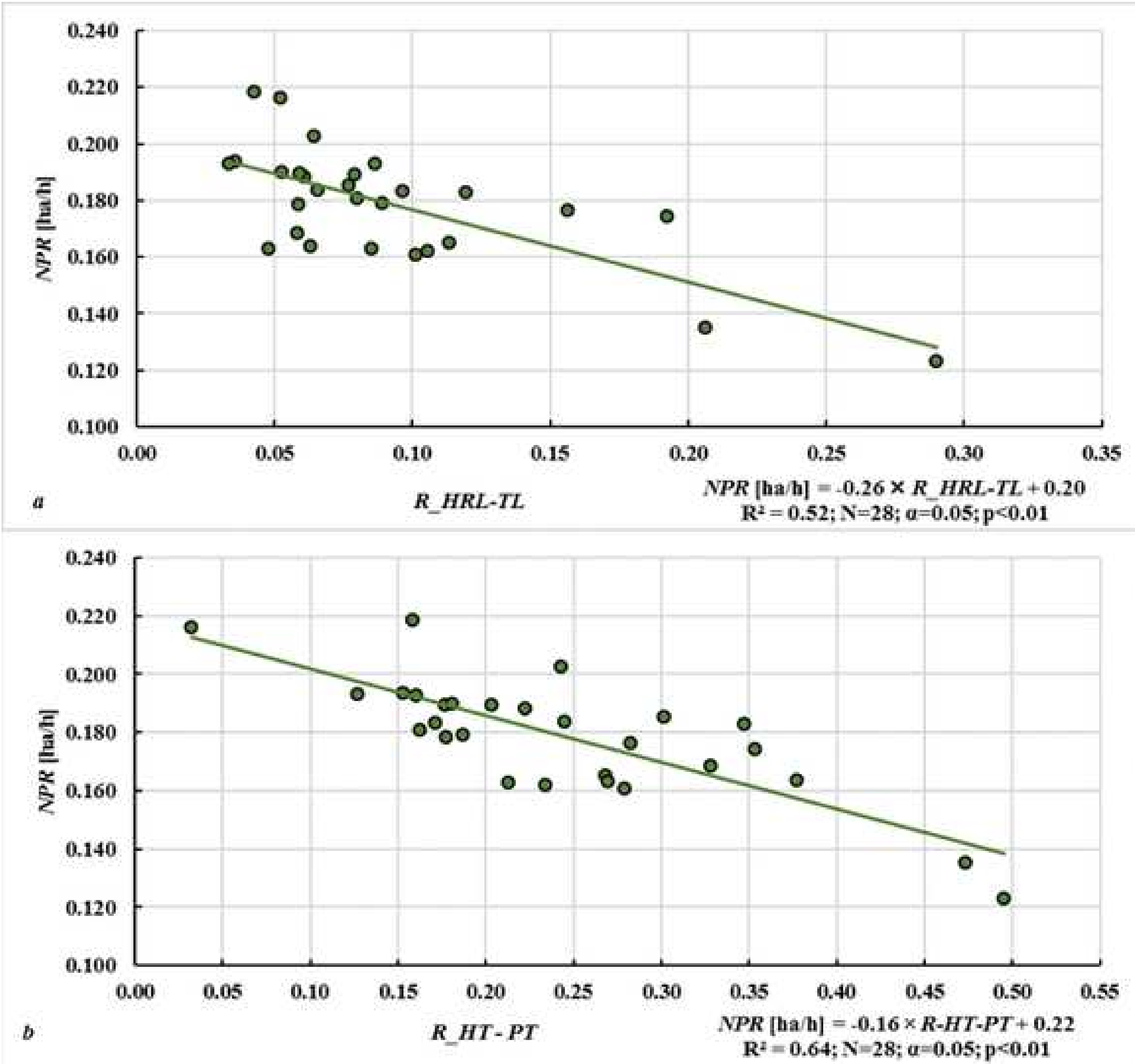


Figure 5



12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Time [hours]
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
Operated area [hectares]
TST [h] = 7.58 × OA [ha] - 0.33
R² = 0.97; N=28; α=0.05; p<0.01
PT [h] = 5.62 × OA [ha] - 0.21
R² = 0.98; N=28; α=0.05; p<0.01
PT* [h] = 5.85 × OA [ha] - 0.13
R² = 0.98; N=28; α=0.05; p<0.01
RT [h] = 3.89 × OA [ha] + 0.02
R² = 0.98; N=28; α=0.05; p<0.01
HT [h] = 1.73 × OA [ha] - 0.22
R² = 0.78; N=28; α=0.05; p<0.01
RT
HT
PT
PT*
TST

Figure 6


0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
NPR [ha/h]
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
a
R_HRL-TL
NPR [ha/h] = -0.26 × R_HRL-TL + 0.20
R² = 0.52; N=28; α=0.05; p<0.01
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
NPR [ha/h]
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
b
R_HT - PT
NPR [ha/h] = -0.16 × R-HT-PT + 0.22
R² = 0.64; N=28; α=0.05; p<0.01