Growth of the perennial energy crop giant reed (*Arundo donax* L.) simulated with ARMIDA, a modified version of the LINTUL model

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Abstract: *Giant reed is a high-yielding perennial herbaceous crop showing a promising potential as energy crop. To evaluate this potential the ARMIDA model was devised as a modified version of the LINTUL model, enabling multiyear simulations and allowing radiation use efficiency to vary within the growing season. To calibrate and validate giant reed development and growth in potential production conditions we used three years of data from an experiment carried out in the Po Valley in a stand of giant reed growing under optimal environmental conditions. Development and biomass allocation of giant reed are regulated by a thermal sum with base temperature T_{base}= 12.7 °C. Leaf area index predictions matched observations (RMSE = 0.66 m^2 m^{-2}) with maximum values greater than 10 m^2 m^{-2}. Aboveground dry matter (stems and leaves), whose yields exceed 40 Mg ha^{-1}, agreed with observed data (RMSE = 2.78 Mg ha^{-1} and 0.83 Mg ha^{-1} respectively). In the Po Valley, giant reed prominently grows only up to the first week of August. From simulations we deduce that radiation intercepted till beginning of August is the main factor conducive to final yields.*
Keywords: *Dynamic simulation, Thermal sum, Radiation Use Efficiency, Biomass partitioning, Potential production, Lignocellulosic species.*

Riassunto: *La canna comune è una coltura erbacea perenne con un promettente potenziale per fini energetici. Per valutare questo potenziale è stato ideato il modello ARMIDA come versione modificata del modello LINTUL, adattandolo per simulazioni pluriennali con Radiation Use Efficiency variabile durante la stagione vegetativa. Per calibrare e validare lo sviluppo e la crescita della canna in condizioni potenziali di produzione abbiamo usato tre anni di dati da un esperimento condotto in pianura Padana in un impianto di canna cresciuta in condizioni ambientali ottimali. Lo sviluppo e l'allocazione di biomassa della canna comune sono guidati da una sommatoria termica con temperatura di base posta a 12.7 °C. L'indice di area fogliare, con valori oltre i 10 m^2 m^{-2} è in accordo con le osservazioni (RMSE = 0.66 m^2 m^{-2}). La biomassa epigea (fusti e foglie), le cui rese superano i 40 Mg ha^{-1}, riproduce bene i dati osservati (rispettivamente RMSE = 2.78 Mg ha^{-1} e 0.83 Mg ha^{-1}). Nella valle del Po, la canna comune cresce principalmente fino alla prima settimana di agosto. Dalle simulazioni deduciamo che la radiazione intercettata fino all'inizio di agosto è il principale fattore che contribuisce alle rese finali.*
Parole chiave: *Simulazione dinamica, unità di calore, Radiation Use Efficiency, ripartizione della biomassa, produzione potenziale, specie lignocellulosiche.*

1. INTRODUCTION

Giant reed (*Arundo donax* L.) is a tall, perennial, rhizomatous grass widely spread in many warm and temperate areas of the world (Lewandosky *et al.*, 2003). Giant reed requires few agronomic inputs, it is tolerant to biotic and abiotic stresses and it is very competitive against weeds. Its floral sterility is an advantage to prevent uncontrolled propagation; moreover, as stated by Ragauskas *et al.*, (2006), the substantial energy saved by the crop in avoiding formation and filling of the reproductive structure is redistributed to the other organs improving final yields. All these features make giant reed, which already accounts for many other uses (Papazoglou *et al.*, 2005), an ideal crop for energy purposes.

Several papers focus on giant reed characteristics, but few of these are devoted to crop modeling. Thornby *et al.*, (2007) and Graziani and Steinmaus (2009) modeled giant reed as invasive species on riparian regions growing in clumps. The potential of the species as a field crop was only recently approached in literature by Stella *et al.*, (2015) by adapting the Canegro model.

Dynamic simulation models are effective tools in agriculture to investigate the crop features. Their main purpose is to simulate crop growth and development. Nevertheless the degree of detail of each one is different. One interesting way of classification of models is the one proposed by Passioura (1996):

– model can be defined as "*Science*" or "*Engineering*". Scientific models have the purpose to improve

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insight on system behavior whereas engineering models make use of robust empirical relations to solve practical problems.

– *Engineering* models are simpler, based on few data and empirical formulas, avoiding the constraints of scientific models (Shibu *et al.*, 2010; Spitters, 1990) and providing a more practical option to assess crop yield. In potential production conditions, i.e. in the absence of biotic and abiotic stresses, the rate of dry matter accumulation can be assumed proportional to the solar radiation intercepted by green foliage (Monteith, 1977). Dry matter production is then derived from the intercepted radiation by means of a conversion factor, named Radiation Use Efficiency (RUE).

ARMIDA (ARundo and MIscanthus Development and Assimilation), is a simple model developed to simulate the perennial herbaceous energy crops giant reed and mischantus (Volta *et al.*, 2012). In this article we limit ourselves to the description of the model for giant reed. Rhizomes are not represented in the model, as simulation is restricted to the aboveground biomass. ARMIDA is conceptually based on the LINTUL1 model (Spitters, 1990). LINTUL1 simulates potential crop production by converting incident Photosynthetically Active Radiation (PAR) into dry matter through a constant RUE (van Oijen, 1992). LINTUL resulted a successful tool to simulate different crops such as potato (Spitters and Schapendonk, 1990), grassland (Schapendonk, 1998; Rodriguez *et al.*, 1999), maize (Farré *et al.*, 2000), oilseed rape (Habekotté, 1997), crambe (Mathijssen and Meijer, 1995), grain amaranth (Gimplinger and Kaul, 2009) and rice (Shibu *et al.*, 2010). Unlike the original LINTUL1, coded in Fortran, ARMIDA is written in the C++ programming language and enables multiyear simulations, with RUE value changing within the growing season (Patel *et al.*, 1999). In this paper we present the ARMIDA model providing also its parameterization and validation for giant reed, comparing simulated aboveground dry matter and Leaf Area Index (LAI) with field observations.

2. MATERIAL AND METHODS

2.1. The experiment

Details of the site and experiment were presented in Ceotto *et al.*, (2013) and are briefly summarized here. The field is located in Anzola dell'Emilia in the alluvial Po river plain, Northern Italy (Lat. 44° 32' N, Lon. 11° 11' E, 38 m a.s.l.). Soil is loam-silty, classified as Udifluventic Haplustepts fine silty, mixed mesic (Soil Survey Staff, 2003). The climate is temperate sub-continental; the experimental site is about 100 km far from the Adriatic Sea. Mean annual rainfall in the years 1991-2008 was 734 mm (Marletto *et al.*, 2010). The estimated depth of the local shallow water table varies from 1.1 m in winter to 2 m in summer (Tomei *et al.*, 2010).

A giant reed stand was established in March 2007 by transplanting rhizomes. Initial stand density was 2.78 rhizomes per square meter. The size of the giant reed stand is 23 x 42 m, corresponding to an area of 966 m^2. This relatively large surface was chosen in order to avoid edge effects which commonly have a substantial effect on giant reed yield in small plots. The crop was fertilized once a year with 120 kg N ha^{-1} in the form of urea and with 120 kg P_2O_5 ha^{-1} in the form of superphosphate; no irrigation was applied.

The aboveground dry matter of stem and leaves, and LAI were measured during the growing season: seven times in 2009, and nine times in both 2010 and 2011. On each sampling time, three destructive samples of aboveground biomass were collected at random in representative areas of the crop stand. The sampled area was 0.5 x 1.0 m = 0.5 m^2. LAI was measured with a Delta-T leaf area meter WinDIAS image analysis system. Dry weights of leaves and stems were determined after oven drying at 105 °C until the reaching of a constant weight.

The aboveground biomass of the whole stand was harvested once per year at the beginning of March. From observations we determined the RUE value referred to the three years experiment and the values of light extinction coefficient and Specific Leaf Area (SLA) only referred to 2011.

We used daily data of temperature and global radiation coming from a meteorological station located beside the giant reed stand. During the three years of experiment weather variables showed substantially different patterns. We consider the period May 1st– October 31st. The cumulated daily mean temperature and global radiation of 2011 (T_{2011} and R_{2011}) were compared with those of 2009 and 2010. The differences of mean air temperature were: T_{2011} - T_{2009} = -68.8 °D and T_{2011} - T_{2010} = +235.9 °D. The differences in incident global solar radiation were: R_{2011} - R_{2009} = +175.6 MJ m^{-2} and R_{2011} - R_{2010} = +314.3 MJ m^{-2}. Overall, the growing season 2010 was cooler and with less incident radiation than the other two seasons, whereas 2009 showed a similar (to 2011) temperature pattern, whereas radiation was substantially lower.

Precipitation patterns during the same period were different among the three seasons. Compared with the 30-year average of this period (368 mm), the cumulated precipitation were: -39% in 2009, +25% in 2010 and -17% in 2011.

2.2. Model description

ARMIDA is a simple and practical model developed to simulate perennial crops over a multiannual time series. Conceptually this is based on the LINTUL1 model (Spitters, 1990) developed by the school of the late Prof. De Wit in Wageningen, NL. As its ancestor, ARMIDA computes the potential crop growth at daily steps. Potential production conditions mean that crop growth occurs under optimal supply of water and nutrients in a pest-, disease- and weed-free environment, under the prevailing weather conditions. Thus, under the above-cited ideal conditions, dry matter production can be assumed proportional to the intercepted PAR, avoiding a more mechanistic and detailed description of the photosynthetic process. In ARMIDA the proportionality factor, i.e. the RUE, can vary within the growing season to reproduce correctly the observed "summer slump" of giant reed growth (Ceotto *et al.*, 2013). In the first phase of growing, LAI depends only on the leaf growth parameter μ and on the effective temperature through the exponential function LAI(day) = LAI(day-1)exp(μ(T-Tbase)). From LAI = 0.75 m^2 m^{-2} onwards its behavior depends on the allocation of dry matter to leaves. Partition of dry matter is regulated by the phenological stage which depends on empirical calibrated rates which are function of a temperature sum. The thermal sum (T_{sum}) is calculated as $\Sigma((T_{min} + T_{max})/2 - T_{base})$, only if $(T_{min} + T_{max})/2 > T_{base}$.

Leaf senescence is driven by the phenological stage and, if LAI exceeds a certain threshold, by shadowing effects too. Unlike LINTUL1, ARMIDA enables to set either the crop emergence DOY (Day Of Year) or to establish a thermal sum threshold above which the crop starts to grow. In this work emergence is defined in the latter way, see below for details.

Daily weather variables needed for model simulations are minimum and maximum temperature (°C), and global radiation (MJ m^{-2}). In addition, the partition dry matter tables depending on the thermal sum and the same list of parameters of LINTUL1 are required (C.T. De Wit Graduate School for Production Ecology, 1997).

Outputs of ARMIDA are values of LAI, dry matter accumulation partitioned among leaves and stems, and further variables useful to assess energy balance of biomass crops, such as cumulated intercepted global radiation and cumulated PAR.

2.3. Software implementation

The software is structured in two main parts: 1) a core consisting of the calculation algorithm; 2) a graphical user interface. The former is written in C++ language in a modular form and can be called from an interface as well as easily embedded into other models. A graphical user interface, written using QT Creator 5.1 (Blanchette and Summerfield, 2006), is distributed to provide a complete operational tool. The interface reads weather data and crop parameters from external files, then calls the algorithm previously built as a static library. Results are either displayed on the screen or saved in external files in .csv format.

Remarkably, the full software distribution is multiplatform and self consistent. Since the model runs at daily time scale, computational time is negligible.

2.4. Software availability

ARMIDA is distributed as free software. It is available for the scientific community with LGPL license (GNU General Public License, 2007) and can be requested to the corresponding author of this paper.

2.5. Model parameterization

Calibration of model parameters was performed for giant reed using data collected in the year 2011 because for this year we have a more complete set of experimental parameters. In the simulations, RUE and the light extinction coefficient were determined experimentally as reported in Ceotto *et al.*, (2013). In the first part of the growing season, approximately from DOY = 120 to DOY = 215, RUE was set equal to 5.74 g MJ^{-1}; however from DOY = 215 onwards, RUE was set equal to 1.5 g MJ^{-1}. As previously stated, in ARMIDA the RUE varies within the growing season in order to reproduce correctly the observed "summer slump" in giant reed growth.

The abrupt change of RUE was fixed at DOY= 215 on the basis of three years of data reported by Ceotto *et al.*, (2013). However, it is plausible that a proper simulation of the crop in different environment would require calibration of both RUE values and DOY of beginning of RUE change. These parameters can be easily calibrated in ARMIDA.

Also the extinction coefficient value, set at 0.3 and the SLA value, set at 0.01 m^2 g^{-1}, were taken from observations. The base temperature of giant reed was set equal to T_{base} = 12.7 °C, as proposed by Graziani and Steinmaus (2009).

The crop starts to grow when T_{sum} > 70 °D (crop emergence) calculated from January 1st of the simulated year. The upper bound of the effective

temperature for computing T_{sum} was set at 30 °C (Nassi o Di Nasso *et al.*, 2011).
The set of further parameters used for simulations were determined by means of minimizing the root mean square errors of aboveground cumulated biomass (leaves and stems) and LAI through a "trial and error" procedure.
The full set of parameters used to run the model for giant reed is reported in Tab. 1.
All calibrated parameters resulted in the range of those present in LINTUL1 for cereals, except leaf growth rate in the juvenile stage μ that we set at 0.3°C^{-1} , i.e. two order of magnitudes greater than for wheat or maize (see LINTUL1 tables of parameters). We justify this, together with a big initial biomass allocated to leaves and stems, by the fact that giant reed is a perennial rhizomatous crop with high amount of resources stored underground in the rhizomes, whereas cereals start the seasonal growth from a small seed. It clearly appears that most of the biomass is allocated to stems starting from an initial 60% up to 100% at the end of the growing season. Aboveground biomass accumulation is partitioned between stems and leaves depending on T_{sum} as shown in Fig. 1. The rates shown in Fig. 1 were calibrated. T_{sum} is calculated from emergence onwards. Validation of the model was carried out by running the model in the years 2009 and 2010 at the same experimental site. The validation dataset cannot be considered totally independent because data were collected on the same giant reed stand during 2009 and 2010.

2.6. Evaluation model indicators

In order to evaluate the model performance, we selected six indices after the cluster analysis conducted by Rocca *et al.*, (2013). Statistics were obtained comparing observed data with the simulation outputs. The estimators evaluated are: Mean Bias Error (MBE) (Addiscott and Whitmore, 1987), Root-Mean-Square Error (RMSE) (Fox, 1981), modeling Efficiency (EF) (Nash and Sutcliffe, 1970), Pearson's correlation coefficient (r) (Addiscott and Whitmore, 1987), coefficient of determination (R^2), and the slope (m) of the linear regression passing from the origin of the observed (x-axis) vs. simulated (y-axis) graphic.

3. RESULTS AND DISCUSSION

3.1. Leaf area index

Leaf area index is one of the key variables to understand the high giant reed yields. In fact, because the canopy extinction coefficient of giant reed is quite low compared to common row crops

Parameter	*Value*	*Unit*	*Reference*
Base temperature	12.7	°C	Graziani and Steinmaus, 2009
Upper threshold of daily mean temperature for assimilation	30	°C	Nassi o Di Nasso *et al.*, 2011
LAI at emergence	0.03	$m^2\ m^{-2}$	Calibrated
Specific Leaf Area	0.01	$m^2\ g^{-1}$	Observed
Growth rate during exponential development	0.3	$°C^{-1}\ d^{-1}$	Calibrated
Critical LAI for death due to shading	9.2	$m^2\ m^{-2}$	Calibrated
Maximal death rate due to shading	0.03	-	LINTUL1 value for wheat
PAR extinction coefficient	0.3	-	Ceotto *et al.*, 2013
Radiation Use Efficiency (DOY < 215)	5.74	$g\ MJ^{-1}$	Ceotto *et al.*, 2013
Radiation Use Efficiency (DOY ≥ 215)	1.5	$g\ MJ^{-1}$	Calibrated
Initial stem biomass	220	$g\ m^{-2}$	Calibrated
Initial leaf biomass	100	$g\ m^{-2}$	Calibrated
Thermal sum at crop emergence	70	°D	Graziani and Steinmaus, 2009
Day of early growth	unused	DOY	-
Senescence threshold	1350	°D	Calibrated (value calculated from crop emergence)

Tab. 1 - Parameter values for giant reed in the ARMIDA model.
Tab. 1 - Parametri relativi ad arundo nel modello ARMIDA.

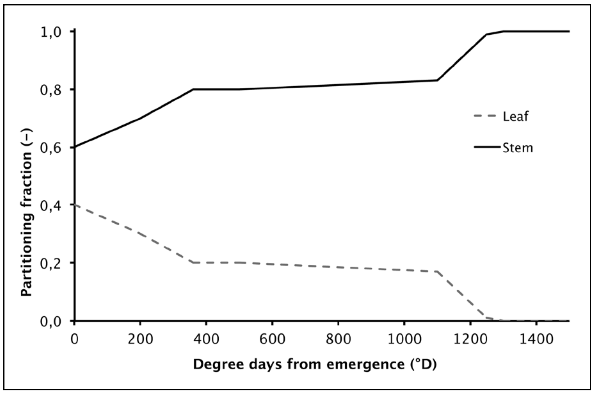

Fig. 1 - Partitioning fraction of leaves and stems as a function of T_{sum} calculated from emergence.
Fig. 1 - Frazione di ripartizione di foglie e fusti, rappresentata in funzione della T_{sum} calcolata dall'emergenza.

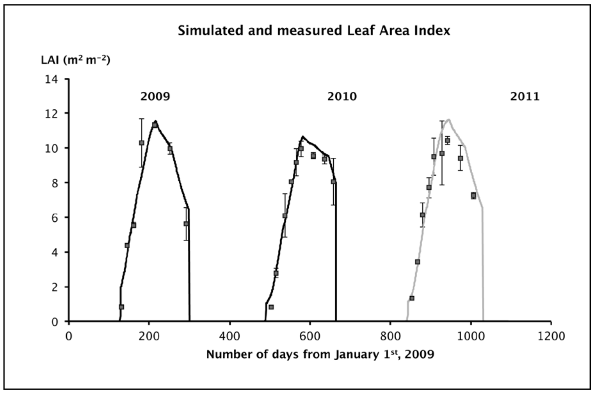

Fig. 2 - Comparison between observed data (squares with related error bars) and simulated data (solid lines) of leaf area index. Black line refers to validation years whereas gray line to calibration year. Error bars refer to the sampling standard deviation.
Fig. 2 - Confronto tra dati osservati (quadrati con le relative barre di errore) e simulati (linee continue) di indice di area fogliare. La linea nera si riferisce agli anni di validazione mentre la linea grigia all'anno di calibrazione. Le barre di errore si riferiscono alla deviazione standard del campionamento.

(i.e. 0.3), PAR interception is saturated at high values of LAI, and even the leaves at the bottom of the canopy are well irradiated and contribute substantially to photosynthesis. In Fig. 2 we show the evolution of LAI along the three experimental years. Giant reed is a macrothermal crop and starts the vegetative development late in mid spring with a very steep growth function. This is likely due, at least for the first days, to the reallocation of reserves from rhizomes to the aboveground organs, rather than to radiation interception and conversion into leaves dry matter. The maximum value of green LAI, exceeding values of 10 m^2 m^{-2}, is reached around DOY = 215. After this date, the LAI starts to decay. Simulation resulted in good agreement with observed data, in particular in the growing phase. During leaf senescence LAI is slightly overestimated.

3.2. Aboveground biomass production

The model simulates satisfactorily the course of dry matter accumulation into leaves and stems. The behavior of green leaves dry matter (Fig. 3, lower lines) is quite similar to that of LAI since giant reed SLA is roughly constant during the growing season. Unlike LAI, leaves dry matter is slightly underestimated during senescence. Its maximum value, more than 10 Mg ha^{-1} is reached around DOY = 215.
Most of the aboveground dry matter is accumulated in stems (Fig. 3 upper lines). Dry matter increases very fast until DOY = 215, showing parabolic trends of growth. After DOY = 215 the growth continues albeit at a lower rate because of the drastic RUE reduction.

3.3. Analysis of weather

As stated above, base temperature was set at 12.7 °C. In 2011, i.e. the calibration year, emergence occurred on April 20th, about 2 weeks earlier than in the other seasons. The model simulated satisfactorily the date of emergence and the subsequent time course of LAI, as well as leaves and stems dry matter accumulation. In 2009, the day of emergence occurred on May 7th, in 2010 on May 3rd and in 2011 on April 20th.

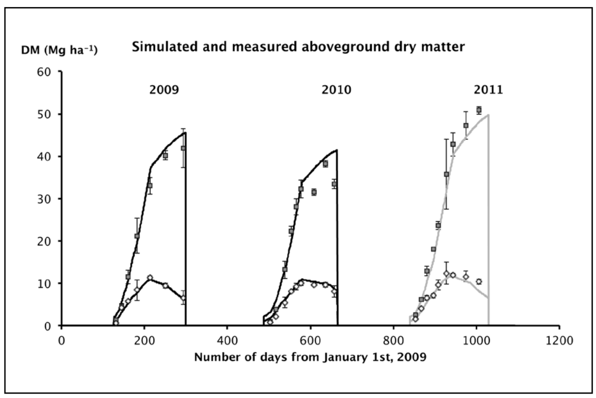

Fig. 3 - Comparison between observed data (squares with related error bars) and simulated data of leaves dry matter (dashed lines) and stem dry matter (solid lines). Black lines refer to validation years whereas gray lines to calibration year. Error bars refer to the sampling standard deviation.
Fig. 3 - Confronto tra dati osservati (quadrati con relative barre di errore) e simulati di sostanza secca fogliare (linee tratteggiate) e sostanza secca dei fusti (linee continue). Le linee nere si riferiscono agli anni di validazione mentre le linee grigie all'anno di calibrazione. Le barre di errore si riferiscono alla deviazione standard del campionamento.

In Fig. 4, we plotted T_{sum} during the growing season, with T_{sum} starting on the day of emergence.
In 2009 the crop compensated the delayed early growth because of a very hot May. Late spring and summer show no relevant differences with respect to 2011. Year 2010 appears to the plant definitely colder than the other two years, if considered in terms of development. Indeed, in 2009 and 2011 T_{sum} exceeded 1500 °D, whereas in 2010 1300 °D were hardly reached.
Intercepted and lost PAR are plotted in Fig. 5. Incident PAR is the sum of intercepted PAR and lost PAR. We observe that the intercepted PAR in 2009 was lower than in 2011. Remarkably at DOY = 215, i.e. the time when RUE drastically drops, in

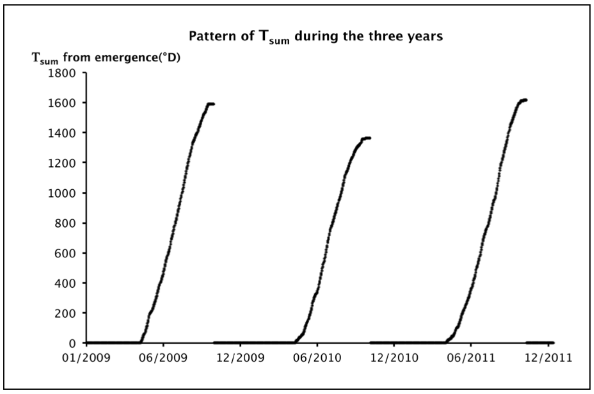

Fig. 4 - Tsum computed from emergence during the growing seasons for 2009-2010-2011.
Fig. 4 - Tsum calcolata dall'emergenza durante le stagioni vegetative 2009-2010-2011.

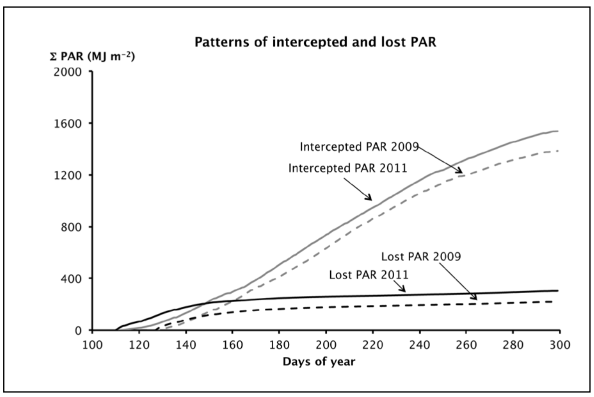

Fig. 5 - Cumulated values (from April, 19) of intercepted PAR (dashed lines) and lost PAR (solid lines) for the years 2009 (gray lines) and 2011 (black lines) are shown. Data of 2010 are not shown for sake of clarity.
Fig. 5 - Valori cumulati (dal 19 Aprile) di PAR intercettata (linee tratteggiate) a PAR persa (linee continue) per gli anni 2009 (linee grigie) e 2011 (linee nere). I dati relativi al 2010 non sono presenti per semplificare la rappresentazione grafica.

2009 cumulated intercepted PAR = 810 (MJ m^{-2}) whereas in 2011 cumulated intercepted PAR = 896 (MJ m^{-2}). These data together with the common value of RUE explain the noticeable difference in yield among years.
The lost PAR of 2009 is higher than 2011 because of the delay in crop emergence.

3.4. Model Performance

In Tab. 2 we summarize through statistical estimators the main performances of the model analyzed on the three quantities discussed in the previous sections, i.e., LAI and aboveground dry matter divided into leaves and stems.
The model resulted a powerful tool in reproducing the time evolution of LAI and dry matter of both leaves and stems in giant reed. LAI was well simulated, only slightly overestimated in 2010 from DOY = 215 onwards. This is confirmed by the slope (m = 1.04) of the observed vs. simulated LAI regression line. Indices MBE (0.32), RMSE (0.66), EF (0.96), r (0.98) and R^2 (0.96) show very good values for simulations.
Leaves dry matter is very well represented by the model. In this case we get the best performance from late spring up to midsummer. The model offers the best performance in simulating stem biomass. Although the stem RMSE (2.78 Mg ha^{-1}) is in absolute terms larger than that of leaves (RMSE = 0.83 Mg ha^{-1}) we have to consider also that final stem dry matter is about four times larger than leaves dry matter. All other estimators, except for MBE, result better in this case.

3.5. ARMIDA as diagnostic tool

By means of ARMIDA we can better understand how giant reed accumulates aboveground biomass. ARMIDA simulates the biomass accumulation taking into account only two weather variables, daily temperatures and radiation. From Fig. 4 we see that, from the point of view of thermal sums, years 2009 and 2011 resulted similar. Nevertheless final yields (stems) in these seasons are 41.9 and 50.8 Mg ha^{-1} respectively. This difference is only attributable to the difference in intercepted PAR (Fig. 5). In 2011 the day of emergence occurred about two weeks earlier than in 2009. This advantage brought to accumulate more aboveground biomass in spring 2011. In addition, as explained above, giant reed from the first week of August onwards drastically reduces RUE independently from other environmental conditions so that few chances to recover the initial gap would have been possible in 2009. This simplified version of the model doesn't

Indicator	LAI ($m^2\,m^{-2}$)	Leaf DM ($Mg\,ha^{-1}$)	Stem DM ($Mg\,ha^{-1}$)	Source	Optimal value
MBE	0.32	-0.07	0.44	Addiscott and Whitmore, 1987	0
RMSE	0.66	0.83	2.78	Fox, 1981	0
EF	0.96	0.93	0.97	Nash and Sutcliffe, 1970	1
r	0.98	0.97	0.98	Addiscott and Whitmore, 1987	1
R^2	0.96	0.94	0.97	-	1
m	1.04	0.97	1.01	-	1

Tab. 2 - Statistical indicators used to evaluate model performance.
Tab. 2 - Indicatori statistici usati per valutare l'efficienza del modello.

take into account biomass partitioning to and from rhizomes and roots. Future improvement of the model will consider implementation of the belowground biomass simulation dynamic.

4. CONCLUSION

The availability of a simulation tool to assess potential yield of giant reed can help in its evaluation as a biomass crop in agricultural environments. We developed ARMIDA, a model to simulate biomass accumulation of giant reed, deriving it from a preexisting model (LINTUL1), with some improvements to accommodate for the perennial character of the plant and also for its variable RUE. The parameterization of ARMIDA on field data from year 2011 gave good crop simulation of giant reed in validation years 2009 and 2010. In particular the time course of both LAI and aboveground biomass accumulation were accurately predicted. Only during senescence the model slightly overestimated LAI and underestimated leaf biomass with respect to observations. Nonetheless the quality of results was not affected, in particular for our main purpose, that is obtaining a correct final biomass yield assessment. Since most of dry matter is partitioned in stems, small errors in simulating leaves biomass become negligible. Further improvements are needed to simulate giant reed growth in suboptimal environments, where either water or nutrients are lacking during most or part of the growing season.

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