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Review Paper

Reviewing the harvest index estimation in crop modeling

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ABSTRACT- Harvest index (HI), ratio of seed yield to aboveground dry matter, is a very important parameter for estimating seed yield in several crop models. In this study, the importance, definition, variability and estimation methods of HI in crop models were discussed. HI estimation methods are categorized into two groups including: (i) complex methods that estimate HI from the beginning of seed growth to crop maturity, dynamically and (ii) simple methods that estimate the final HI at crop maturity. HI is a trait that is affected by many environmental parameters and the genotype of a crop. Soil water content or soil water suction during growing season, soil nutrient, groundwater depth, high air temperature, plant population and irrigation water salinity are some environmental factors affecting the HI. Therefore, in all models that used HI to estimate crop yield, either complex (e.g., AquaCrop model) or simple method, the harvest index estimating equations should be calibrated by changing the genotypes or cultivars, environmental and non-environmental parameters.

INTRODUCTION

Yield Estimation

There are several methods to estimate the seed yield in crop models. Soltani et al. (2005) divided these methods into three groups: 1) estimation of the number of seeds per unit area and the rate and duration of seed filling, 2) using dry matter partitioning coefficients to estimate seed yield accumulation and 3) seed yield obtained by product aboveground dry matter and harvest index. However, there are other methods to predict the seed yield. Azizian et al. (2015), Mahbod et al. (2015), Majnooni-Heris et al. (2011), Zand-Parsa et al. (2006) and Zand-Parsa (2001) estimated grain yield by grain nitrogen uptake divided by grain nitrogen concentration. The third method is the most common method and is used in many studies to simulate crop yield, e.g., Ahmadi et al. (2015) and Sepaskhah et al. (2011) for maize; Talebnejad and Sepaskhah (2016) for quinoa, Moosavizadeh-Mojarad and Sepaskhah (2011) for rice, Shabani et al. (2015) and Shabani et al. (2014) for rapeseed, Mahbod et al. (2014) for wheat.

Harvest Index

Harvest index is calculated as the ratio of grain yield to total aboveground dry matter. Improving harvest index (HI) resulted in considerable increases in crop yields during the twentieth century. It is a very important parameter in plant breeding. The major goal in breeding is attaining higher crop yield through selection of a cultivar with higher harvest index (Gutam, 2011). However, Evans (2013) mentioned that crop selection based on improving photosynthesis is better than HI criteria. Plants need leaves to capture light and roots to absorb water and nutrients for growth and stems to form the leaf canopy and support the flowers and grain. Therefore, in order to increase potential yield, it is necessary to increase HI along with increasing total biomass. Different definitions have been given for HI by agronomists and plant physiologists. Agronomists define HI as the ratio of machinery harvested yield to total aboveground dry matter (Talebnejad and Sepaskhah, 2016; Shabani et al., 2013; Abbasi and Sepaskhah, 2011; Shabani et al., 2010; Unkovich et al., 2010; Sinclair, 1998; Prihar and Stewart, 1990; Richards and Townley-Smith, 1987). Machinery harvested yield is any part of plants which can be harvested and has economic value. Plant physiologists define HI as a measure of the relative investment of plant resources in reproductive parts, and this is usually determined based on a plant and may include pod walls and other non-seed components (Unkovich et al., 2010; Aranjuelo et al., 2013). Also, the harvest index is the physiological efficiency and ability of a crop for converting the dry matter into economic yield (Sharifi et al., 2009). Economic yield includes seed mass for grain crops (e.g., corn, wheat and other cereal crops), root mass for root crops (e.g., carrot, sugar beet, turnip, etc.), shoot mass for vegetative and forage crops (e.g., alfalfa, lettuce, etc.) and stigma mass for saffron. Agronomists only consider the aboveground dry matter. It is in contrast to the view point of the physiologists that consider total plant dry matter including both the root and shoot dry matter.

Improved cultivars increased grain yield along with lowering or no changing of the total dry matter which resulted in higher values of HI. Wheat HI increased about 0.015 per decade in Australia and 0.2 in the United Kingdom from 1880 to 1997 (Unkovich et al., 2010). Austin et al. (1980) reported that winter wheat production increased by 70kg/ha/year from 1948 to 1978 in the United Kingdom. Newer cultivars have similar dry matter production in comparison with the older ones and their higher HI is the main attribute for increasing grain yield (Austin et al., 1980; Calderini et al., 1995).

Harvest Index Variation

Harvest index is different for plant species and even between different genotypes of each plant species (Wnuk et al., 2013; Abbasi and Sepaskhah, 2011). Cereal crops have higher HI compared with legumes and oilseed plants. Determinate crops have higher values and lower variation of HI than indeterminate crops (Unkovich et al., 2010). Wnuk et al. (2013) presented the scatterplot matrix for harvest index (HI), grain and biomass yields for seven winter wheat cultivars (Fig. 1). Fig. 1 shows that for different genotypes of wheat, grain yield was not related to HI (Fig.1a), while it shows a quite strong linear positive relationship with biomass yield (Fig.1c). Also, HI and biomass yield were negatively related in a linear way (Fig. 1b). However, when looking into particular cultivars, this conclusion does not have to be held. For example, in Grana, the relation between HI and grain yield was a clear line with positive slope. In MA77/97, this relation also existed, but with a negative slope (Wnuk et al., 2013).

Contrary to common HI definition, it is not dependent on grain yield and total dry matter. In other words, grain yield is dependent on HI and total dry matter (Wnuk et al., 2013; Wang et al., 2011). Therefore, HI is a trait that is affected by environmental parameters including soil water content or suction during the growing season (Abbasi and Sepaskhah, 2011; Shabani et al., 2013), soil nutrient (Majnooni-Heris et al., 2011; Sinclair, 1998; Moser et al., 2006), groundwater depth (Talebnejad and Sepaskhah, 2013; Shabani, 2011), high air temperature (Prasad et al., 2006; Challinor et al., 2005), plant population (Moosavizadeh-Mojaradand Sepaskhah, 2011; Tollenaar et al., 2006), irrigation water salinity (Shabani et al., 2015; Azizian, 2013) and genotype of a plant (Wnuk et al., 2013; Richards and Townley-Smith, 1987). With respect to Turner et al. (2001) studies, Unkovich et al. (2010) mentioned that environmental parameters rather than genotype are considered as the major determinant of harvest index for most field crops.

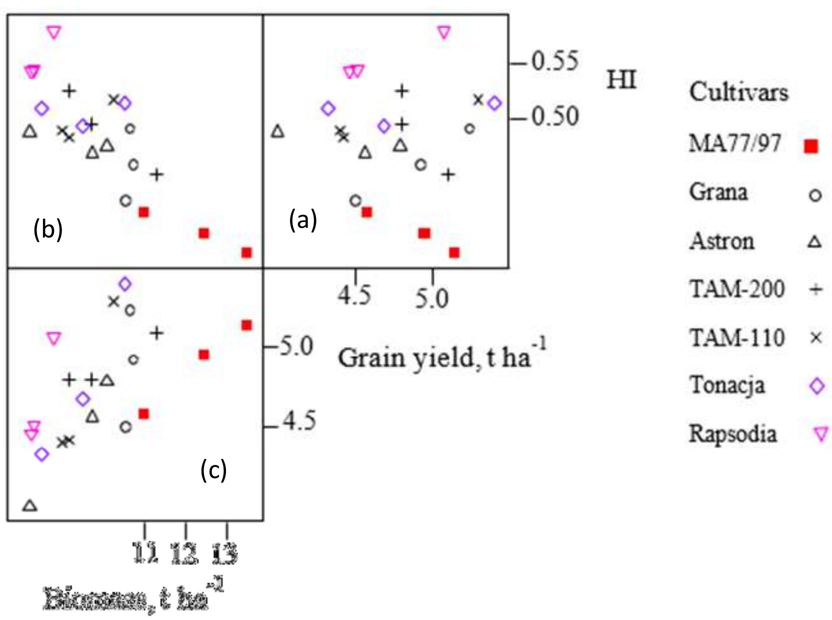

Fig. 1. Scatterplot matrix for harvest index and grain yield (a), harvest index and biomass (b) and biomass and grain yield (c) among seven winter wheat cultivars (Wnuk et al., 2013).

Determining Harvest Index in Crop Models

There are two methods to estimate HI in crop models. These methods are: (1) dynamic HI estimation from the beginning of seeds growth to maturity, (2) estimating the HI at the time of grain maturity.

Dynamic HI Estimation

In this method, harvest index is assumed to increase linearly as a function of time after the beginning of seed growth with a constant rate (dHI/dt) as follows (Sinclair, 1986):

$$HI_t = HI_{t-1} + \frac{dHI}{dt} \quad (1)$$

Where HI_t and HI_{t-1} are HI at t and (t-1) days after the beginning of seed growth. Soltani et al. (2005) proposed when severe soil moisture depletion occurs and the extractable soil water ratio is below a threshold value, the daily increment of HI is zero, during grain filling period. They mentioned the threshold value as 0.1 for cowpea.

In contrast to constant daily increments of HI, Kemanian et al. (2007) proposed the exponential model that relates HI to the fractional post-anthesis phase growth (f_G) as follows:

$$HI = HI_x - (HI_x - HI_0).\exp(-k.f_G) \quad (2)$$

Where HI_x is the asymptote, HI_o is the intercept and k is a constant relating the rate of change of HI with respect to f_G. Furthermore, Challinor et al. (2005) determined the rate of HI changes with respect to time by pod-setting factor (fraction of flowers that produce setting pods). Pod-setting factor is dependent on the critical air temperature which the pod-set begins to be affected and the temperature at zero pod-set.

In AquaCrop model, HI was estimated from flowering (starting yield formation) or tuber initiation to physiological maturity as follows (Vanuytrecht et al., 2014):

$$HI = f_{HI}HI_x \quad (3)$$

Where HI_x is the reference value of HI at physiological maturity under non-stress conditions and f_{HI} is the adjustment coefficient of HI as a function of soil water content and air temperature. In other words, HI was only adjusted based on soil water depletion and air temperature during yield formation and the effect of other environmental parameters. Salinity, fertilizer application, groundwater depth, and plant population on HI were not considered in AquaCrop model. Therefore, HI cannot be precisely estimated by AquaCrop model when salinity, fertilizer application, groundwater depth, and plant population affect it.

Seed yield estimation in each day after the beginning of seed growth is the major advantage of Equations (1) and (2).

HI at Grain Maturity

In all crop models, estimation of final grain yield is the major goal. In many of these models, final grain yield was estimated by the product of final aboveground dry matter and final harvest index at maturity. There are several methods to estimate the dry matter. For example, in the MSM model (Zand-Parsa et al. 2006), hourly top dry matter weight was simulated by considering corrected intercepted solar radiation with air temperature by maize leaves, root N uptake, and radiation use efficiency. In some models, dry matter production is determined as a function of transpiration and the difference of saturated and actual vapor pressure (Sepaskhah et al., 2013; Shabani et al., 2015; Yarami and Sepaskhah, 2016). AquaCrop used multiplication of the cumulative actual crop transpiration during the growing season and normalized water productivity for simulating total biomass (Steduto et al., 2009). In CERES model, dry matter is determined based on intercepted photosynthetically active radiation by plant leaves. In WOFOST and SWAP models, dry matter accumulation is estimated by the rate of gross CO_2 assimilation of the canopy. This rate depends on the radiation energy intercepted by the canopy which, as in the case of CERES and MSM, is a function of incoming radiation and leaf area (Eitzinger et al., 2004). Also, Ziaei and Sepaskhah (2003) presented a model according to which, dry matter is a function of pan evaporation. In empirical models, dry matter was estimated based on evapotranspiration (Sepaskah and Ilampoor, 1996; Sepaskhah and Ghasemi, 2008; Sepaskhah and Beirouti, 2009; Azizian and Sepaskhah, 2014; Sepaskhah and Yarami, 2016), growing degree-day (Mahbod et al., 2014), and number of days after planting (Shabani et al., 2014; Sepaskhah et al., 2011). Final HI is a function of transpiration (Sepaskhah and Ilampour, 1996; Sepaskhah et al., 2013), actual evapotranspiration and other environmental parameters that affect HI as mentioned above. In other words, as mentioned by Wnuk et al. (2013) and Wang et al. (2011), all parameters that affect plant transpiration, actual evapotranspiration and plant growth also affect HI. Therefore, there are many empirical relations to estimate HI as a function of environmental parameters (Table 1). It is shown in Table 1 that HI depends on several parameters including: plant stover nitrogen uptake, sum of nitrogen application rate, soil residual mineral nitrogen, seasonal applied water, rainfall, groundwater depth, plant population, seasonal transpiration, crop water stress index, electrical conductivity of groundwater, soil water suction head, and irrigation water salinity. In other words, all parameters that affect plant growth can affect HI. This issue was not considered in the well-known AquaCrop model so that HI was only adjusted to water stress and air temperature in this model although HI was a function of experimental factors (Table 1).

Table 1. Harvest index as a function of different parameters*

Plants	Equation	Cultivar	Experimental factors	Reference
Rice	$HI=-4E\text{-}06(Ph)^2 + 0.0009(Ph) + 0.3636$	Bamati-385, F-Malakand and Pukhraj	Ph	Amanullah and Inamullah (2016)
Maize	$HI=-0.0000095(NU)^2+0.004(NU)+0.1598$	SC704	N and I	Zand-Parsa (2001)
Wheat	$HI=2.705(I+R)-3.94\times10^{-3}(N+N_r)-2.2899(I+R)^2+4.82\times10^{-6}(N+N_r)^2+1.956\times 10^{-3}(I+R)^2(N+N_r)$	Shiraz	N and I	Mahbod et al. (2014)
Rice	$HI = -0.000415(GD) +0.399$	Ghasroddashti	GD	Shabani (2011)
Rice	$HI=-0.15+0.0106(P)+0.838(W/W_m)-0.476(W/W_m)^2$	Champa-Kamfiroozi	N, IM, I and P	Moosavizadeh-Mojarad and Sepaskhah (2012)
Saffron	$HI=3.0\times10^{-5}(T)$	Unknown	IM, II	Sepaskhah et al. (2013)
Cowpea	$HI=0.47-0.18(CWSI)$ $HI=2.37\times10^{-4}(T_1)^{0.5}$	29005	I	Sepaskhah and Ilampour (1996)
Rice	$HI=0.159+6.5\times10^{-5}(GD)-0.004(WS)-0.39(IF)^2+0.45(IF)$	Ghasroddashti	GD, WS and I	Talebnejad and Sepaskhah (2016)
Rice	$HI=0.365-3.84(h)$	Ghasroddashti	II	Abbasi and Sepaskhah (2011)
	$HI=0.472-1.41(h)$	Cross-Domsiah		
	$HI=0.291-3.93(h)$	Hasani		
	$HI=0.359-2.18(h)$	Rahmat-Abadi		
Maize	$HI=0.82(I_1)+4.7\times10^{-4}(N+N_r)-0.35(I_1)^2+5.2\times10^{-3}(S)^2-9.60\times10^{-7}(N+N_r)^2+2.87\times10^{-3}(I_1)^2(S)^2$	SC704	N, S and I	Azizian (2013)
Rapeseed	$HI=-0.0012(I+R)+0.000688(S)^2-1.8\times 10^{-6}(I+R)(S)^2+1.48\times10^{-6}(I+R)^2+0.525$	Talaieh	I and S	Shabani et al. (2015)
Maize	$HI=1.009I-0.547I^2+0.00016N\times I$	SC704	I and N	Sepaskhah et al. (2011)

(*) Notes: Ph is the Phosphorus (kg hm^{-2}), NU is plant Stover nitrogen uptake (kg ha^{-1}), $N + N_r$ is the sum of nitrogen application rate plus soil residual mineral nitrogen (kg ha^{-1}), I + R is the seasonal applied water plus rainfall (mm), GD is groundwater depth (mm), P is the plant population in number of hills per m^2, W is the seasonal amount of applied irrigation water (mm), W_m is the maximum amount of applied water used in continuous flooding irrigation (mm), T is the seasonal transpiration (mm), CWSI is crop water stress index, T_1 is the seasonal transpiration (kg ha^{-1}), WS is the electrical conductivity of groundwater (dS m^{-1}), IF is the ratio of applied irrigation water depth to full irrigation water depth, h is the soil water suction head (cm), S is the irrigation water salinity (dS m^{-1}), I_1 is the seasonal applied water (m), IM is the irrigation methods includes basin and furrow irrigation systems, II is the irrigation interval, SC is the single cross.

Considering the salinity factor by Azizian (2013) in their experiment compared with the Sepaskhah et al. (2011) study resulted in the addition of the salinity term in HI equation. For the given rice cultivars (e.g., Ghasroddashti cultivar), HI was not a function of a simple parameter (i.e., transpiration). Further parameters were included in the HI equation by changing the environmental parameters; for example, groundwater depth (Shabani, 2011; Talebnejad and Sepaskhah, 2016), groundwater salinity (Talebnejad and Sepaskhah, 2016) or irrigation interval that affects the soil water content or soil water suction head (Abbasi and Sepaskhah, 2011). Therefore, as mentioned by Unkovich et al. (2010), environmental parameters rather than genotype are considered as the major determinant of HI and the effect of these parameters should be considered in crop modeling. On the contrary, there was no specific relation between HI and leaf area index, dry matter and yield although they have a direct relation with evapotranspiration or transpiration. Therefore, crop models should be calibrated based on limiting parameters of plant growth, plant species and even plant genotypes to estimate HI in each location and environmental condition. Contrary to the advanced models (e.g., CropSyst, CRPSM, CERES, CSM-CROPGRO and AquaCrop) that are complex, difficult to understand and suffer from lack of input data, the simple models can estimate the crop yield easily.

The major advantage of the simple models is that they are easy to use for practical applications due to using simple equations and fewer input data (Sepaskhah et al., 2013). However, these models should be calibrated in different locations, cultivars and climate conditions.

CONCLUSION

Contrary to common HI definition (ratio of seed yield to total dry matter), HI is not dependent on grain yield and total dry matter. In other words, grain yield is a dependent variable and HI and total dry matter are independent variables. In this study, methods to estimate HI in crop models were categorized into two groups. The first group including the methods that dynamically estimate the HI from beginning seed growth to maturity and the second group include estimation of the final HI at grain maturity. HI is a trait that is affected by environmental and crop genotype parameters. Therefore, in all models that used HI to estimate crop yield, either complex or simple model, the harvest index estimating equations should be calibrated by changing the genotypes or cultivars, environmental and non-environmental parameters.

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مقاله مروری

مروری بر تخمین شاخص برداشت در مدل سازی گیاهی

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واژه های کلیدی:
مدل سازی گیاهی
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چکیده- شاخص برداشت، نسبت محصول دانه به وزن ماده خشک گیاه، یک پارامتر مهم برای تخمین محصول دانه در بسیاری از مدلهای گیاهی است. در این مطالعه، در مورد اهمیت شاخص برداشت، تعریف، متغیر بودن و روشهای تخمین آن در مدل های گیاهی بحث شده است. روش‌های تخمین شاخص برداشت به دو دسته تقسیم‌بندی می‌گردند. ۱) روش‌های کامل: روش‌هایی که به صورت پویا مقدار شاخص برداشت را از زمان شروع رشد دانه تا رسیدگی کامل تخمین می‌زنند. ۲) روش‌های ساده: روش‌هایی که مقدار شاخص برداشت نهایی را در زمان رسیدگی دانه تخمین می‌زنند. شاخص برداشت ویژگی است که تحت تاثیر بسیاری از عوامل محیطی و خصوصیات ژنوتیپ گیاه قرار دارد. رطوبت خاک یا مکش آب خاک در طول فصل رشد، مواد مغذی خاک، عمق آب زیر زمینی، دمای بالای هوا، تراکم گیاهی و شوری آب آبیاری از عوامل محیطی هستند که بر شاخص برداشت گیاه موثر می‌باشند. بنابراین در همه مدلهایی که از شاخص برداشت جهت تخمین محصول استفاده می‌شود – هم مدل های کامل مانند مدل AquaCrop و هم مدل های ساده- با تغییر ژنوتیپ یا رقم، عوامل محیطی و غیر محیطی معادلات تخمین شاخص برداشت می‌بایست واسنجی گردند.