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A CRITICAL ANALYSIS OF "HARVEST INDEX"

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نقد تحليلي لتعين واستخدام دليل المحصول

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تم حصر وذكر الطرق المتعددة التي يستخدم فيها أحد معايير تقييم انتاجية المحاصيل الزراعية ألا وهو دليل المحصول ، كذلك تم اختيار وابراز قيم دليل المحصول لنباتات منزرعة وغير منزرعة من شتى بقاع العالم .

حدد البحث الارباك والفوضى عند حساب دليل المحصول حيث اشار إلى ان بعض الباحثين قد يُضمن وزن الجذر في المقام والبعض يكتفي بالمادة الحياتية النباتية فوق سطح الأرض في المقام وفي كلتا الحالتين سوف تتغير النسبة أو دليل المحصول .

أشارت نتائج البحث إلى أنه وبالرغم من الاستخدام الشائع لدليل المحصول في معظم البحوث التي تنشر عن انتاجية المحاصيل الا أن بعض هذه الاستعمالات تكون تارة في غير مكانها وتارة أخرى غير ضرورية وزائدة وقد تكون خطأ وبالتالي قد تقود إلى إخفاء أهم نتائج البحث . ان دليل المحصول « نسبة » وبالتالي فهي خاضعة للخطأ في مكونيها الاثنين البسط والمقام وحيث أنه معلوم من علم الاحصاء أن « النسب » لا توزع توزيعاً معتدلاً وبالتالي لا يصح اطلاقاً تحليل نتائج دلالة المحصول الواحد بواسطة تحليل التباين الاحصائي .

ان المزارع في حاجة إلى مرشد زراعي لكي يقدم النصح والمشورة في انجع الوسائل وأحسن الخدمات الزراعية من ري وتسميد وكثافة وميقات زراعة ومكافحة آفات وطرائق الحصاد الآلية وغيرها وليس المزارع في حاجة إلى معرفة دليل المحصول الأحسن أو الأسوأ .

وقد قدمت مقترحات في هذا البحث عن كيفية استعمال دليل المحصول . ويستخلص البحث أن استعمال الزيادة أو النقصان في النسبة المئوية لانتاجية أي محصول قد يكون أبسط وافيد من الناحية العملية في حين يتعذر استعمال دليل المحصول ، وان يقتصر استعمال دليل المحصول في أضيق نطاق وفي البحوث الاكاديمية البحتة فقط .

Key Words: Abuse, biological yield, economic yield, good use, harvest index, sources of variation, yield components.

ABSTRACT

The many ways in which harvest index ratio (HI) can be used are discussed. A selection of published values for HI are given. Attention is drawn to the confusion in calculating the HI such that some present methods of assessing HI may distort the results. Despite the claims made for HI, and its widespread use throughout much of the literature, its use in some cases is superfluous and may obscure some kinds of information. As a ratio, it is subject to error in both components, and is most unlikely to be normallly distributed, so that normal analysis of variance will not be valid. A farmer needs to know the probability of achieving a given margin of returns over costs rather than unnecessarily knowing or quoting a HI. Suggestions are made as to when and where to use the HI. Emphasis is placed on adopting percentage increase of response between yields rather than using HI.

INTRODUCTION

Since the introduction of various growth relations in crops, such relationships as "a 1000-seed weight-grain number m^{-2} - fertilizer efficiency-lodging resistance-grain yield-straw yield (above ground biomass) - biological yield and harvest index" agronomists, crop physiologists and plant breeders have extensively applied them and have found them useful means in quantification of yields of differnt crops. The concepts have, to date, become known with different terminologies: agronomic characters - yield components - yield attributes and morphophysiological traits. Because there are many kinds of crops (with cultivars or varieties) with varying periods of germination, establishment and maturity, and life span, their economic yields cannot be assessed by a single agronomic method. So loose is the concept of harvest index ratio (HI) that some workers are not adhering even to one method of calculating it. It is not unusual to see authors discuss differences in harvest indices among and between crops in the text of an article, suggesting that they are indeed the better measure to use. This has unfortunately, led to spurious predictions and conclusions. Many papers simply refer to harvest index without defining what it means; others present straightforward and unviersally accepted definitions. This paper examines various published harvest indices which were intended by their authors to distil the essential aspects of yield to a single reliable value and so enable higher yield to be distinguished form lower yield; and outline the ailments and shortcomings from which the harvest index suffers.

Basic Concepts:

Nichiporovic (1954) introduced the terms (a) "biological yield" (Y_{biol}) for the total dry matter production, and (b) the "agricultural or economic yield" (Y_{econ}) which comprises the grain or the fibre or the tuber or the fruit. Nichiporovic suggested a relationship between the (Ybiol) and the (Y_{econ}) as "the coefficient of effectiveness of formation of the economic part of the total yield" so that:

$$(Y_{econ}) = (Y_{biol}) \times K \qquad (1)$$

Donald (1962) introduced the term harvest index HI to replace Nichiporovic's coefficient of effectiveness so that equation (1) becomes:

$$(Y_{econ}) = (Y_{biol}) \times HI \qquad (2)$$

i.e.

$$Y \text{ (Weight of grain)} = Y \text{ (weight of above ground biomass + weight of grain)} \times HI \qquad (3)$$

Therefore,

$$\log Y_{(econ)} = \log Y_{(biol)} + \log HI \qquad (4)$$

A higher harvest index indicates a superior conversion of dry matter to grain yield. Many workers currently (Sharma and Smith, 1987; Eck, 1988; Sharma and Mittra, 1988) calculate HI for grain crops as a percentage, thus:

$$HI = \frac{\text{grain yield}}{\text{biomass yield (straw weight + grain weight)}} \times 100\% \qquad (5)$$

At first sight, an increase in $Y_{(biol)}$ leads to a decrease in HI.

Much of the reproted variation in HI is due to whether Y is taken (a) on a dry weight or a fresh weight basis, or (b) to include or exclude roots, or (c) to include or exclude fallen leaves - litter fall is substantial in potatoes or (d) to include or not to include a stubble e.g. in cereals. It is not surprising, therefore that the results from published work show great variability. However, HI remained a heuristically important variable as an indelible criterion for selection for yield analysis of cereal and root crops (Donald and Hamblin, 1987; Kawano *et al.*, 1982; Green, 1984).

Sources of variation in HI:

Table 1 shows the HI ratios represented for some crop species and most of them have ratios well below 50%. There can be a large variation due to various factors.

1. Between crop species (growth habit):

Practical difficulties are often encountered in the calculation of HI of many crops. For example, the HI determination for crops like tomatoes, cotton, and broad beans, becomes tedious as the fruit of such plants do not set or ripen simultaneously, i.e. the extended flowering phase leads to a range of seed maturities at harvest. When determining HI the economic products (marketable yields) of many crops are extremely varied: e.g. cotton (lint and seed), rubber (latex), gum-arabic (cortex sap flowing from cut), coconut (fruits), tea (leaves), oil palm (fruit branches), potatoe (tuber), sugar beet and cassava (roots). The application of HI to sugar-cane gives highly varying results (Irvine, 1983, p. 372-373). For example, with sugar stuff, the product of most interest, the HI is 19%. If syrup, gur, or molasses are manufacutred in addition to sucrose then HI = 23%. If the fibre in the sugar-cane stalk is used as fuel, then the final HI is 63%. The differences between the species may be associated with the different growth habits as it can be noted that HI of root and tuber crops > HI of grain crops and the HI of water-melon *(Citrullus vulgaris)* is ≥ 90. Tanaka (1983, p. 75) indicated that root crops and potatoe tubers have a higher HI because the growth period of organs to be harvested is long relative to the crops total growth period. Egli *et al.,* (1985) admitted that HI vary across cultivars, growth habits and planting dates.

2. Between genotypes or between cultivars within a crop species (genetic variation within trials):

Unlike most other crops, wheat has undergone intensive selection and breeding for high grain yield. So protean is the value of HI that some values of the same cultivar vary considerably, e.g. the cultivar Kalyansona (wheat) has HI between 34-53%. It's of interest to note that semi-dwarf variety N67 with short straw, few leaves and very large ear has the highest HI (Ephrat *et al.,* 1964). Gent and Kiyomoto (1989) found a similar result to that of Ephrat *et al.* (1964) while they were studying HI in relation to two semidwarf cultivars of wheat (see Table 1 and their Table 1) as compared to two tall varieties. The two authors concluded that there was an inverse relationship between stem height and HI. The variation noted for HIs of wheat may be due to (a) differences in environment due to disease, pests or stress conditions and (b) harvesting methods adopted in the trials.

3. Between environments:

Amir (1989) reported variations in HI of several cultivars and hybrids of sunflower (Helianthus annuus) in response to two irrigation regimes (Table 2). In sunflower production areas where the crop depends primarily on stored soil moisture, and as the rainy season terminates, drought stress increased during crop maturity. This may explain the relatively poor yield (HI) of sunflower to regularly irrigated area. Similar results were obtained for irrigated wheat compared to rainfed wheat, (Passioura, 1977; Whitfield *et al.,* 1989). Sharma *et al.* (1987) experimenting with 10 winter genotypes indicated that both HI and grain yield are significantly affected by environmental changes.

4. Plant Density, plant size and reproduction

Literature regarding the impact of plant density on HI is not in agreement. For example, the high HI (see Table 1) of cotton genotype 2086 was the result of low dry matter allocation to both leaves and stems as a result of low plant density. Kirby *et al.* (1990) pointed out that high plant density "resulted in more dry matter in leaves and stems relative to furit and thereafter low HI".

Particularly controversial has been the rate of plant size on time of reproduction and subsequently the value of HI. Gardener and Gardener (1983) argued that (1) a minimum plant size was required for Sorghum before it started to produce grain, (b) as Sorghum plants increased in size, a large portion of the dry mattter was grain, and (c) the harvest index was dependent on dry weight per plant. Prihar and Stewart (1990, 1991) presented evidence contrary to Gardener and Gardener (1983) by stating (1) the harvest index was independent of size of mature producing grain plants, (2) HI might increase as plant size may decrease, (3) stress rather than plant size may finally determine HI, (4) there is no relation between HI and plant size as such.

Harper (1977) argued that reproduction entails a cost to plants that is reflected in reduced growth. Reekie and Reekie (1991) manipulated with gibberellic acid to control time of reproduction in *Oenothera biennis* (a short-lived monocarpic perennial, i.e. time of reproduction is variable) and found that (a) reproduction does not necessarily reduce growth and in fact it may enhance growth, and (b) the effect of reproduction on growth may help determine the size and age at which reproduction takes place. Reekie and Reekie (1991) results do not support a certain minimum plant size in order reproduction commences.

5. Confused methods of assessing HI:

Many different and confused methods to calculate HI have been observed in recent published literature. To name but a few: Okelana and Adedipe (1982) experimenting with cowpea wrote at the footnote of their Table 5 "harvest index is the seed weight expressed as a percentage of total plant weight" and thereafter they calculated HI by including the root weight as part of the denominator. At first glance this approach of calculating HI is at variance with the previous concept shown in equation 1-5. Lucas (1981) calculated HI of maize using the following formula:-

$$\text{Harvest Index} = \frac{\text{dry weight of grain}}{\text{total crop dry weight}} \qquad (6)$$

The denominator in Lucas's formula is subject to error in that the root weight might have been included. In relation to HI calculation de Riddler *et al.*, (1981) wrote "root weights have not been determined, because of the laborious methodology involved and the uncertainty in interpreting the data obtained". This is not to say that correct and acceptable definitions of HI are not available for different crops, for there is a plethora of them. For example, Harper and Ogden (1970) stated "Harvest index was defined as the ratio of the economically important portion of the yield, usually grain, to the total biological yield of dry matter ......, but biological yield has been taken to mean the weight of above ground-parts at the time of harvest". Innes *et al.*, (1981) experimenting with the winter wheat, stated that "The grain and straw were dried at 80° C and weighed and the harvest index of each plot was caluclated as the ratio of grain yield to total above ground dry matter". Siddique, Kirby and Perry (1989) investigating the physiological basis of increased grain number per ear in some old and modern wheat varieties wrote "Harvest index was calculated as the ratio of grain-yield to total above-ground biomass".

What are the factors which control HI?

A high harvest index for a certain crop indicates its improved physiological efficiency in partitioning or exporting a substantial portion of assimilates towards grain fillling and subsequent formation (source-sink relationship).

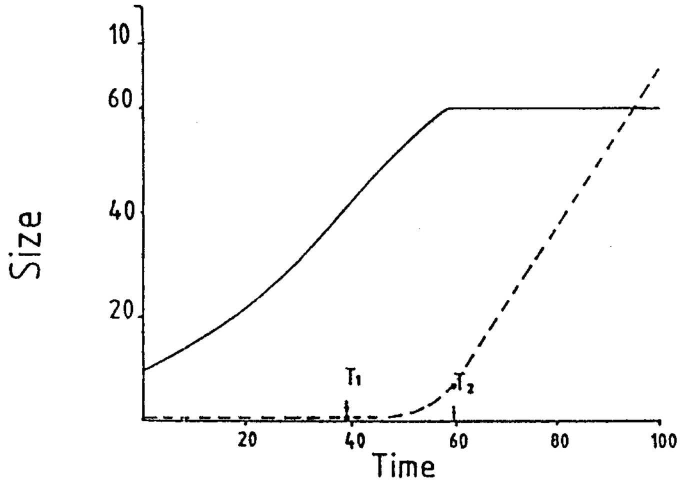

Fig. 1: The optimal pattern of growth of the vegetative (solid line) and reproductive (dashed line) parts. Two switching points are denoted by T_1, and T_2 in the period (T_1, T_2) mixed allocation of energy takes place, i.e., both vegetative and reproductive growth occur simultaneously. (From Kozlowski and Zioloko, 1988).

Arnon (1972) indicated that variations in the distribution of dry matter between different plant parts is not fully understood. Hunt (1988) indicated that above - or below - ground environmental stresses cause root-shoot partitioning in favour of the affected part of the plant, i.e., nutrient limited plants may become more 'rooty' and shaded plants more 'shooty'. Most harvest indices have been calculated for annual plants (Table 1). At the end of a growing season annual plants leave seeds, but perennials leave seeds, the root system and the shoot system (Tateno and Watanabe, 1988). Perennials have a much more complex growth due to several complicating factors i.e. unlike annual plants, perennials need to store energy for perennation. In most annual species vegetative growth continued during the reproductive phase. Amongst the factors which determine the distribution of assimilates within a plant are (a) the change from vegetative to reproductive growth in most crops - e.g. broad bean - was accompanied by remarkable alterations in the pattern of assimilate distribution (Ismail and Sagar, 1981), and (b) the vascular interconnections between source leaves and sinks (Mullins, 1970; Ismail, 1984). In the indeterminately flowering crops, e.g. a few varieties of soybean, tomatoes and cotton, a proportion of the dry matter produced after flowering is used to make new leaves rather than to fill reproductive sinks (Ismail and Khalifa, 1987; Khan and Sagar, 1969; Ashley, 1972). The preferential allocation of resources to vegetative rather than reproductive structures may be wasteful in that individual annual crop plants are unlikely to survive until a subsequent year. Beech *et al.* (1988) outlined the causes which make some strawberry varieties poor in yield by stating "some strawberry cultivars grown commercially in the United Kingdom.... are vegetatively vigorous, producing dense foliage and large number of runners, so their harvest index is poor. Reduction of vegetative growth would improve the harvest index and allow assimilates used in the production of leaves or runners to be diverted into crown production ....)". The general inverse relation between reproduction in plants and vegetative growth is agreed upon (Bazzaz *et al.*, 1987). As pointed out by Harper (1977), Bazzaz and Reekie (1986), dry matter partition within a plant depends on the relationship between the vegetative phase and the reproductive phase (and because photosynthesis is a vegetative function) so that structures or activities are alternatives. this discrepancy could reflect the fact that there is a complex relationship during the transition from the vegetative to reproductive phase and that there is no instantaneous switch-over (a bang-bang switch, Fig. 1) between the two phases, i.e the switch to reproduction at the different crop species level is not instantaneous (Cohen, 1971) but a gradual switch (King and Roughgarden, 1982; Koslowski and Ziolko, 1988) thus resulting in different yields. Photoperiodism and vernalization appear to have regulatory effect on vegetative and reproductive growth (Johnson *et al.*, 1960). Egli (1980) pointed out that the harvest index does not relate to changes in partitioning that occur during the vegetative growth of the plant. In view of the documented increase in global CO_2 concentration and expected temperature rise, Baker *et al.*, (1989) indicated that HI in soybean decreased with both increasing CO_2 concentration and air temperature treatments.

Table 1

Accumulated data of HI of some crops and plants under optimal growth conditions

Cultivar Variety or Genotype	Harvest Index %	Reference	
	Cereals Wheat *(Triticum aestivum L.)*		
N 67 (dward variety)	65.0	Ephrat et al	1964
Gai/Rht$_2$	52.0-55	Brooking & Kirby	1981
Gai/Rh$_2$	47.0-47	Brooking & Kirby	1981
Kalyansona	37.0	Sinha et al	1982
Kalyansona	34.0	De et al	1982
Kalyansona	40.9	De et al	1982
Kalyansona	52.0	Rawson	1986
Moti	43.0	Sinha et al	1982
C-306	36.0	De et al	1982
C-306	34.0	De et al	1982
Wadi El-Neel	40.0	Mohamedali	1987
Giza 155	29.0	Mohamedali	1987
Tam 105	44.0	Eck	1988
Honor	31.0	Gent & Kiyomoto	1989
Purcel	44.0	Gent & Kiyomoto	1989
Ticonderoga	51.0	Gent & Kiyomoto	1989
Houser	51.0	Gent & Kiyomoto	1989
	Rice *(Oryza sativa L.)*		
Ratna	50.0	Tanaka	1983
	39.0-42.0	Sharma & Mittra	1988
	Triticale (*X. Triticosecale* Wittmack)		
Group of 20 varieties	32.0	Sinha et al	1982
	Barley *(Hordeum vulgare L.)*		
DTS, 141	33-50	Riggs et al	1981
Ratna	24.0	Sinha et al	1982
	Corn *(Zea mays L.)*		
-	50.0	Tanaka	1983
XL 66	47.0	Ofori & Stern	1986
SR 99	47.0		
PV 76 S	38.0	Hattendorf et al	1988
-	47.0	Muchow	1989
	Oat *(Avena sativa L.)*		
20 different cultivars	38.0-44	Takeda et al	1979
Fg-derived line	45.0	Takeda et al	1980
	Sorghum (*Sorghum bicolor* (L.) Moench)		
-	50.0	Tanaka	1983
Double TX	34.0	Francois et al	1984
NK-265	25.0		
PV 535 GR	39.0	Hattendorf et al	1988
-	36.0	Muchow	1989
	Pearl Millet [*Pennisetum americanum* (L.) Leeke]		
	16.00	Hattendorf et al	1988
	30.0	Muchow	1989
	Legumes Broad Beans *(Vicia faba L.)*		
Maris Bead	35.0-48	Thompson & Taylor	1982
-	45.0	Tanaka	1983
	Cowpea *(Vigna unguiculata L.)*		
Banjo	31.0	Ofori & Stern	1982
	Pigeonpea *(Cajanus cajan L.)*		
Prabhat	31.0	Sinha et al	1982
	Chickpea (*Cicer arietinum L.)*		
JG 65at	31.0	Sinha et al	1982
	Lentils *(Lens culinaris* Medic.)		
Plant L 406	26.0	Ganwar & Singh	1986
Plant L 406	41.0		
Plant L 639	42.0	Sinha & Ram	1986
LG 60	37.0		
LP-12L 639	39.0		
	Peas *(Pisum sativum L.)*		
Filby	42.0-54	Slim et al	1985
Frimas	41.0-56		
Vedette	37.0-52		
	Soybean (*Glycine maxima* Merr.)		
-	45.0	Tanaka	1983
Davis	38.0	Ismail & Khalifa	1987
Semmes	36.0		
Cumberland	34.0	Hattendorf et al	1988
Fiskeby V	61.0		
Collee	25.0		
Lee	25.0	Tsay et al	1988
Bethel	38.0		
	Groundnuts (*Arachis hypogaea* L.)		
-	22.0-29.0	Quoted from de Ridder	1981
-	40.0	Tanaka	1983

Table 1 Contd.

Cultivar Variety or Genotype	Harvest Index %	Reference	
	Pinto Bean (*Phaseolus vulgaris*L.)		
UI 114	32.0	Hattendorf et al 1988	
	OTHERS *Brassica campestris* DC.		
Toria	23.0	Saran & Giri	1987
Toria	35.0	Saran & Giri	1987
Yellow Sarson	27.0	Chauhan & Bhargava	1984
Brown Sarson	28.0		
Yellow	29.0	Sinha et al	1982
Brown	26.0	Sinha et al	1982
	Brassica juncea (L.) Czern.		
Pusa bold	30.0	Chauhan &Bhargava	1984
Pusa bold	26.0	Sinha et al	1982
Pusa bold	24.0	Saran & Giri	1987
	Brassica napus L.		
Bo 15	21.0	Saran & Giri	1987
	Brassica carinata A. Braun		
RK. 8	18.0	Saran & Giri	1987
	Eruca sativa Mill.		
ITSA	19.0	Saran & Giri	1987
	Gossypium hirsutum L.		
Acala SJ-2	47.0	Kerby et al	1990
2086	67.0	Kerby et al	
	Helianthus annuus L.		
	28.0-30	Harper & Ogden	1970
IS907	22.0	Hattendorf et al	1988
	Okra (*Abdlmoschus esculentus* (L.) Moench)		
Clemson spineless	16.0-20.0	Sionit et al	1981
	Root Crops Cassava (*Manihot esculenta* Crantz)		
-	60.0	Tanaka	1983
Genotypes	70.0	corley	1983
M Aus 7	52.0	Tsay et al	1988
	Sweet-Potato (*Ipomoea batatas* (L.) Lam.)		
-	80.0	Tanaka	1983
	Sugar Beet (Beta vulgaris L.)		
-	45.0	Tanaka	1983
	Stem-Tuber crops Potatoes (*solanum tuberosum* L.)		
-	80.0	Tanaka	1983
-	75.0	Spitters et al	1988
	Vegetable Crops Water-melon (*Citrullus lanatrus* ssp. *vulgaris* Schrad) Fursa		
-	89.0-92.-	Ismail-Unpublished data	
	Perennial crops Oil Palm (*Elaeis guineensis* Jacq.)		
	61.0	Corley	1983
	Coconut (*Cocos nucifera* L.)		
-	62.0	Corley	1983
	Rubber (*Hevea brasiliensis* (Willd ex A. Juss.) Müll. Arg.)		
-	37.0	Corley	1983
	Cocoa (*Theobroma cacao*)		
-	30.0	Corley	1983
	Apple (*Malus domestica* Borkh.)		
-	70.0	Avery	1970
-	65.0	Palmer	1988
	Weeds-(*Senecio vulgaris* L.)		
-	26.0-27.0	Harper & Ogden	1970
	Ruderals *Calotropis procera* (Ait.) Ait. Fil.		
-	6.0-8.0	Ismail	1992

Abuse of HI

HI predictions are sometimes useless when one is comparing the overall production between two differnt crops (Yau, 1987 see his Table 2) in order to select one species for an area. It is clear from Yau's results that lines of barley outyielded those of triticale; however, in certain studies HI may be used to explain why a certain crop outyields another crop.

Table 2

Harvest index of sunflower cultivars grown under two systems of production in the Sudan

Cultivar	Nisheishiba (Irrigated System)	Samsam (Rainfed System)
Vniimk 8931	42.0	32.0
Calchin Inta	42.0	30.0
Quayacan Inta	43.0	33.0
Impira Inta	44.0	30.0
Hybrid 8101	56.0	41.0
Hybrid 3107	48.0	44.0
Hybrid 7000	50.0	42.0
Hybrid 7775-8	56.0	43.0

Source: Amir, H. A. (1989).

Although weeds competing with wheat decrease yield, yet Tanji *et al.*, (1987) found that the HI of weed free wheat and weed infested wheat were the same (see their Table 2). Tanji *et al.* (1987) did use HI and biomass in order to analyse the yield differences. It is not clear whether Tanji *et al.*, mean or suggest that if HI is the same then their yields tend to be equal. This is another example of the possible misinterpretation of results from the use of HI ratios. All else aside, HI is a ratio and therefore if the weed-free and weed-infested crops have numerically the same HI, it does not mean they will have the same yield. Spitters (1983b) wrote "Harvest index shows a large random variation: being a ratio of two quantities it includes the error of both quantities ..... one should use the harvest index with caution". Some authors insert HI in their tables without further referring to its significance or function. Bismillah Khan *et al.* (1987) found that in wheat the grain yields between two sowing methods significantly differed, but their respective HI ratios remained the same. (see their Table 3). The authors did not explain the meaning of this. This meant that the competitive abilities of the different sinks were not affected by treatments. However, this illustrates the unneccessary and redundant use of HI by the previous two authors. Eck (1988) experimenting for two years with winter wheat (Tam 105), applied six levels of fertilizer N (0-210 Kg ha^{-1}) with four treatments vis. 1-1 unstressed. 1-2 stressed during heading and grain-filled, 1-3 stressed during tillering and jointing and 1-4 stressed thoughout Spring, but he allowed Fall irrigation for all treatments. Eck's results clearly show that although the grain and straw yields were significantly increased with increase in N the respective harvest indices were erratic (see his Fig. 1 and his Table 3). Eck concluded "Compared to treatment I-I, grain yield were 27, 32, and 52% less on treatments 1-3, 1-2 and 1-4, respectively. Applied N did not affect HI on treatment on 1-1 and 1-3 but reduced them on treatment 1-4 in 1981 .... The significantly higher HI on treatment 1-4 compared to treatment 1-1 in 1982 resulted from the HI on treatment 1-4 being unaffected by N application, while there was a trend towards reduced HI with increasing N applications on treatment 1-4 being unaffected by N application, while there was a trend towards reduced HI with increasing N application on treatment 1-1 (Table 3)". Whilst there is no explantion for such a response in HI, it occured in several, though not all, relevant and similar data.

Good use of HI:

A field and a glasshouse experiment were carried out by Brooking and Kirby (1981) to assess yield in winter wheat genotypes (gai/rht_2 and Gai/Rht_2). Brooking and Kirby (1981) concluded that "Gai/Rht_2 genotypes outyielded all gai/rht_2 genotypes both in glasshouse and field (Table 4). The main stem yield advantage of the Gai/Rht_2 genotypes (21.4% in the glasshouse; 17% in the field) was largely due to a greater number of grains.. In all cases Gai/Rht_2 genotypes had a higher harvest index (Table 4). The observed differences in dry-matter partitioning during ear development were therefore reflected not only in the final number of grains but also in harvest index". Brooking and Kirby (1981) results clearly illustrate the association between yield and HI and therefore their usage of HI in such results is appropriate and justified.

To provide genotypes with different numbers of ears, single plant selections were made (Innes *et al.*, (9181) from F_2 populations of winter wheat crosses in which one of the parents is known to have high (H) and the other low (L) number of ears. Innes *et al.* (1981) wrote "The mean grain yield of the H lines, 8.33 t/ha, was 8% greater than those of the L lines .... The average harvest index of H lines was not significantly greater than that of the L lines (Table 2)". Innes *et al.* (1981) clearly explained the non-association between yield and HI by stating that " ..... the greater grain yield of the H lines was associated with a greater total dry-matter production", and "The lower grain weight per ear H lines resulted from the combined effects of fewer and lighter grains". However, the changes with time in the harvest index of wheat varieties cultivated in Britain during the past half century do provide an interesting indication of the benefit of selection for short straw over this time.

HI or grain/straw ratio?

Attempts to relate the economic yeild divided by the biological yield to a value assigned always to a single crop are not really satisfactory since it is difficult to achieve a single value (Table 1). Gonzalez Ponce (1987), studying competition between wheat *(Triticum aestivum L.)* and the weed *Avena sterilis L.*, in relation to the proximity of their time of emergence, stated that "Then grain weight/straw weight ratio was also affected i.e. through competition, wild oats affected wheat proportionally more in its productivity than in its development". The interesting point in Gonzalez Ponce's study is that if his grain/straw ratios were converted to HI ratios his previous statement will neither be affected nor altered. (see his Table 2).

HI and RE (Reproductive Effort):

HI concept and RE concept, although related, yet they have two different meansings (see de Ridder *et al.*, 1981).

$$HI = \frac{S}{B} \qquad (7)$$

$$RE = \frac{(S+E)}{B} \qquad (8)$$

Where S = total actual seeds/ plants
E = total weight of empty inflorescence or fruit/ plant
B = Above ground biomass = weight of vegetative components/plant + S + E

It is clear that in terms of percentage RE is always greater than HI.

HI and Reproductive Efficiency:

Coffelt *et al.*, (1989) used other methods to estimate yield increases in peanut (Arachis hypogaea) i.e. reproductive efficiency. Five Reproductive Efficiency Methods (REM) were used by Coffelt *et al.*, (1989) using the following formulas:

$$REM\ 1 = \frac{\text{mature pod dry weight}}{\text{plant dry weight}} \times 100 = \text{Harvest index (HI)} \qquad (9)$$

$$REM\ 2 = \frac{\text{mature pod total}}{\text{flower total}} \times 100 \qquad (10)$$

$$REM\ 3 = \frac{\text{pod total}}{\text{flower total}} \times 100 \qquad (11)$$

$$REM\ 4 = \frac{\text{peg total + pod total}}{\text{flowr total}} \times 100 \qquad (12)$$

$$REM\ 5 = \frac{\text{mature seed total}}{\text{2 (flower total)}} \times 100 \qquad (13)$$

Cofflet *et al.*, stated that "Since results for RE estimated by REM 1 were different from the other methods, REM 1 may be measuring a different physiological process than the other methods. Thus, future studies should utilize at least two methods (REM 1 and one other) when estimating RE. Based on our experience, REM 3 would probably be the most reliable and easiest to use of REM 2, 3, 4, and 5".

Is a large HI always an objective of a plant breeder?

Ceccarelli and Mekni (1985) answered this question in relation to barley breeding in dry areas by stating "Where barley is commonly grown and where barley with sheep is the only farming activity..... the barley crop is either grazed by sheep in the field or harvested for animal feed. In either case the commerical as well as the nutritive value of the straw is important. Therefore, genotypes with a large harvest index are not necessarily the desired indeotype to develop for these areas". Moreover, dwarf genotypes may have a high HI but can fail in yield due to a low biomass production.

HI and Competition

Spitters (1983a) pointed out that inter-plant competition [(Intra-specific competition (density response) and inter-specific competition (mixture effect)] was better measured by biomass than by the yield of any plant part because dry-matter distribution within the plant varied with the competitive stress. W.C.H. van Hoof (as quoted by Spitters 1983a and b) estimated the HIs of maize (c.v. Kretek) and groundnuts (c.v. Gajah) by replacement series (mixed cropping and sole cropping) experiments. Spitters (1983b) used W.C.H. van Hoof results and pointed out that yield/biomass ratio did not remain constant but varied with plant density i.e. the HI decreased at high densities (Fig. 2) the HI of maize was much less reduced by inter-specific competition with groundnuts than by intra-specific competition (Fig. 3).

HI and modern varieties:

Rigg *et al.*, (1981) and Siddique *et al.*, (1989) experimenting with barley and wheat respectively clearly stated that the grain yield and HI were generally higher in modern than old varieties. Siddique *et al.* (1989) indicated that there was a strong correlation betweean ear: stem ratio at anthesis and harvest index; they further added that improvements in grain number had occured because the stem competed less than the ear for dry matter. Siddique *et al.* (1989) concluded...... "Selection for high ear: stem ratio at anthesis may lead to further improvement in grain yields". However, Lupton (1982) argued that a high HI should not be the main goal if yield of modern varities is to increase by stating "But the increase in....... yield has bean mainly due to increase in harvest index, with little change in biomass....., it is therefore necessary for breeders to select varieties with increased biomass".

Although Wells and Meredith (1984) indicated that yield improvement of cotton is associated with increased HI and early fruiting, yet Kirby *et al.*, (1990) experimenting with modern cultivars of *Gossypium hirsutum L.* stated that "increasing HI alone does not always result in higher yield. For example, genotypes with superokra leaf morphology had a greater fraction of dry matter partitioning to fruit but no yield improvement, due to increased total matter production".

However, Sinclair *et al.* (11990) indicated that for corn grain yield was closely linked and correlated to the accumulation of biomass; subsequently they calculated HI as follows:

$$G = a + bB \tag{14}$$

$$HI = \frac{G}{B} = b + \frac{a}{B} \tag{15}$$

Where G = grain yield, B = accumulated biomass, and a and b are the intercept and slope, respectively, of the linear regression.

HI or percentage increase in yield?

The HI is not constant for a particular crop or species (Table 1). It is surely misleading by an agronomist or an agricultural extensionalist to quote an HI to a farmer since it implies a fallacious precision. A farmer, for example, might find it helpful to know which of two treatments or options may give him a considerable benefit or a higher yield over the other, rather than unnecessarily knowing the HI. Indeed, Milthorpe and Moorby (1972), stated "Simplicity and interpretability with imperfection are preferable to incomprehensible impeccability".

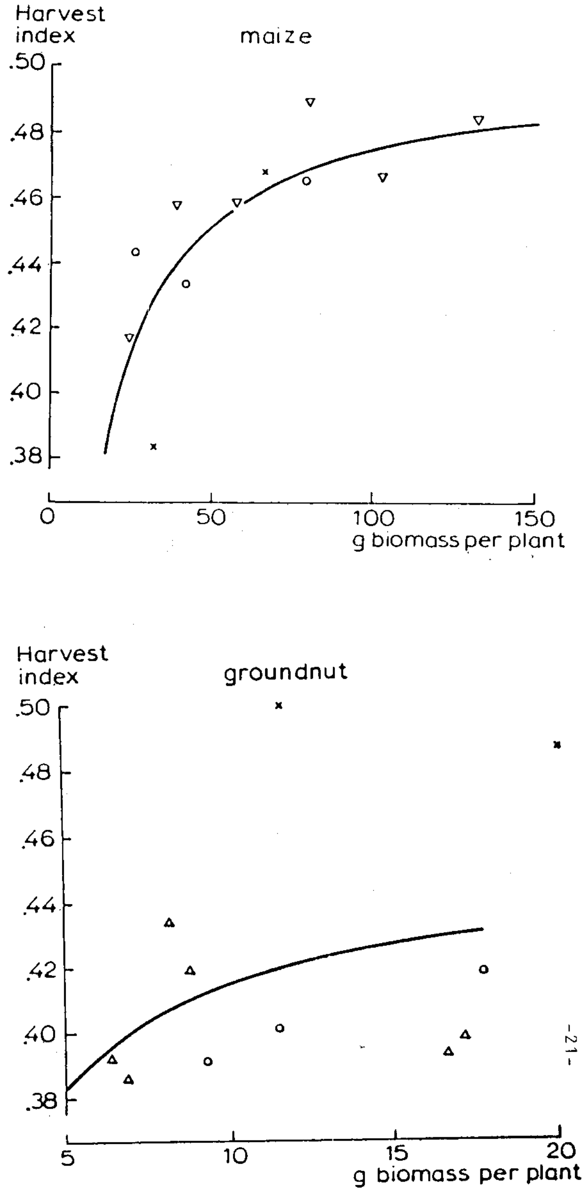

Fig. 2: Relation between harvest index of a plant and its competitive position characterized by the biomass of that plant. The percentage of plants of the species in the total population is represented by: Δ 1-33%, 0 34-66%, Δ 67-99%, and x 100%. (From Spitters, 1983b).

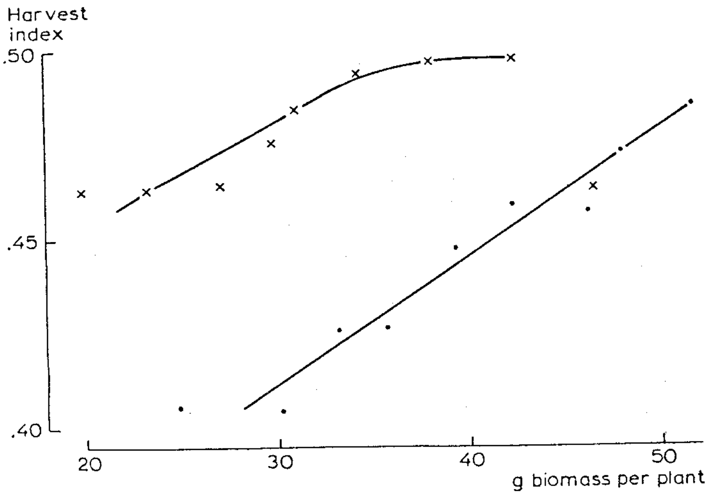

Fig. 3: Relation between harvest index and biomass per plant of maize in sole cropping (•) and in mixture with groundnut plant (x). (From Spitters, 1983b).

A sound and practical alternative to the use of HI (the normal way done by many workers) could be to compare yields (weight/area) after a given treatment using percentage increase treatment respectively. Examination of Table 1 in Mohamedali (1987) reveals that wheat variety Wadi El-Neel outyielded variety Giza 155, with a yield advantage of 20-22% (average of percentage increase for five seasons). Mohamedali stated explicityly "five year results justified the release of the new Wadi El-Neel variety for the Northern Region by the Technical Committee for Variety Release". It is apposite in this context to present that although Mohamedali calculated out the HI of both varieties (Table 1), his recommendations as an agronomist were based on percentage increase in yield rather than using the HI. In a 2-year study Sharma and Mittra (1986) studied the growth and yield of lowland rice in relation to the combined use of organic materials and N fertilizer. Although the two authors found that the HI of the treatments was similar (see their Table 2) yet they agronomically subjected their recommendations to yield response i.e. grain yield in relation to certain fertilizer minus grain yield under no N fertilizer = response (see their Table 5). Sharma and Mittra (1988) results do not show any agronomic advantage by calculating the HI. Mohammedali, (1987), Sharma and Mittra (1988) methods are simple, direct, unambiguous and speedy.

Is there an association between HI and yield?

Results from previous work show that there is no relationship. Sharma *et al.*, (1987) using 10 winter wheat genotypes wrote "Correlation coefficients between HI and grain yield were inconsistent in good and poor environments." Charles-Edwards (1982, p. 106-111) stated explicitly that there is no justification to look for such relationship, "It is concluded that the harvest index adds little to our understanding of crop performance, that a better and meaningful understanding can be obtained by the direct analysis of the main determinants of grain yield....... It is not particularly helpful or meaningful from which that index was derived, grain yield".

DISCUSSION

Donald (1962) defined harvest index (HI) as the ratio of the grain dry weight to the total above ground dry weight (biomass) of a crop at maturity.

Harper and Ogden (1970) and Dantuma and Thompson (1983) indicated that harvest index is a crude character to provide some measure of the partition of assimilate between the economic yield and the biologic yield. Dantuma and Thompson (1983) indicated that there were obvious shortcomings with the measure of total dry weight for determining HI and that there was a need for better understanding of dry weight partitioning in a species. Indeed, they wrote "Until a better definition of harvest index is derived, final total dry matter will probably provide an adequate standard to which to relate seed weight ... therefore, to be valid, comparisons of harvbest index on a purely dry weight basis may need qualifying". However, some simple facts about yield estimate remain controversial. Although Samarrai *et al.*, (1987) concluded that HI can be considered a promising yield selection criterion, Siddiqui *et al.*, (1987) argued that kernel weight may be used as a selection criterion for an early identification of productive mutants in wheat. Sharma and Smith (1987) noted that the HI would provide an incomplete assessment in their crop stands and contended that grain yield is useful for identifying high grain yielding genotypes. These two authors concluded "the results of this study indicate that population density had a significant effect on grain yield and biomass yield but non on HI. Finally, results of this study failed to support the views of certain other workers that HI in thinly seeded populations can be used more effectively than yield *per se* for predicting grain yield in the commercial crop. The additional limitations in using HI and biomass results from the time and labour required to harvest all plant materials and do the extra calculations". Wheat or any other crop are not constrained to grow according to one of the harvest indices specified in advance by agronomists (Table 1) and it must be emphasized that the grain yield is a function of several factors while the biological yield is a function of another set of factors. Both the numerator and the denominator which determine HI vary widely with place, management practices, pests, and crop and are influenced largely by agronomic and ergonomic considerations. Deloughery and Crookston (1979) indicated that popultion density and especially environment must be taken into consideration when evaluating HI information.

Whether or not HI plays a role in the final agronomic recommendations is an unresolved question, although the burden of evidence from this study rests with the view that it does not; but can be a very useful criterion together with total biomass in analysisng differences in yield.

Until agronomists and plant physiologists revise the role of HI and deal with the matters I have alluded to, the use of HI should be kept to a minimum i.e. in evaluating the response of a crop species for certain environmental conditions (Rawson, 1986), when comparing sole crop to intercropping agriculture (Ofori and Stern, 1986; Tsay *et al.*, (1988), as a selection criterion for yield improvements in early segregation generations (Bhatt, 1977), in breeding programmes when evaluating genotypes of one crop (Austin *et al.*, 1982; Brooking and Kirby, 1985; Rines and Halstead, 1988) and its use should be totally discouraged in situations where HI values result in loss of information and produce incorrect data.

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