Influence of climate on durum wheat production and use of remote sensing and weather data to predict quality and quantity of harvests

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Abstract: *Climate conditions severely affect crop production, influencing plant responses and harvest characteristics. For the growers of durum wheat (*Triticum turgidum *L.* var. durum*) an important aspect, in addition to yield, is the grain quality taking into account that it is closely related to the flour properties and therefore to the quality of resulting pasta. The study analyzes the influence of rainfall and temperatures on the winter durum wheat productions and the predictive role of meteorological and satellite indices at large scale (NDVI). Results show a significant negative correlation between precipitation and grain protein concentration. On the other hand, increasing temperatures were associated with grain protein accumulation, while negative correlations were found with kernel specific weight and yield. NDVI recorded during the crop cycle resulted descriptive of all productive variables, showing the suitability to be integrated with the weather information in a local forecasting system.*
Keywords: Triticum durum*, protein content, specific weight, meteorological information, NDVI.*

Riassunto: *Le condizioni climatiche hanno un notevole impatto sulle produzioni agrarie, influenzando la risposta della piante e le caratteristiche del raccolto. Per i coltivatori di frumento duro (*Triticum turgidum *L.* var. durum*) un importante aspetto, oltre alla resa, è la qualità della granella, in considerazione del fatto che questa è strettamente legata alle proprietà della farina e quindi alla qualità della pasta prodotta. Lo studio analizza l'influenza delle precipitazioni e della temperatura sulla produzione di grano duro ed il ruolo che può essere svolto da indici calcolati a partire da dati meteorologici e satellitari su vasta scala (NDVI), al fine di sviluppare un sistema di previsione della qualità e della quantità dei raccolti. I risultati mostrano una correlazione negativa tra le piogge e il contenuto proteico della granella. D'altra parte, temperature crescenti risultano associate ad un accumulo di proteine, mentre determinano una diminuzione del peso specifico e della resa. L'NDVI durante il ciclo colturale è risultato descrittivo di tutte le variabili produttive mostrando l'idoneità ad essere integrato con le informazioni meteorologiche in un sistema di previsione locale.*
Parole chiave: Triticum durum*, contenuto proteico, peso specifico, informazioni meteorologiche, NDVI.*

INTRODUCTION

Winter durum wheat (*Triticum turgidum* L. *var. durum*) production represents approximately 58% of the cultivated wheat in Italy, in contrast it only covers about 9% of the wheat production in European Union (Eurostat, 2009). The Italian winter durum wheat is grown over an area of about 1.3 million hectares with an average yearly production of about 3.5-4 million tons (Eurostat, 2009). This crop provides the raw material for the pasta industry, one of Italy's most renowned products. Val d'Orcia, in Tuscany region, is one of the most suitable areas of central Italy where the cultivation of durum wheat has entered the tradition and it is the basis of typical products (i.e. "Pici"). The qualitative parameters of pasta (i.e. yellow degree, transparency, consistency, good cooking behavior regarding elasticity, stickiness and resistance) are closely related to that of the flour used and therefore of the grains, particularly referring to protein content and gluten quality (Dexter and Matsuo, 1980).

Several researches show that weather conditions, during shooting, grain filling and grain ripening stages, are crucial in determining the quality of harvest for the common wheat (*Triticum aestivum* L.) (Ciaffi *et al.*, 1996) and the study of Dalla Marta *et al.* (2010) and Orlandini *et al.* (2010) on durum wheat highlights the influence of air temperature and rain on grain protein content. In northern Europe, where the climatic

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conditions entail a prolonged grain filling stage, the grains have high specific weight but low proteins concentration; in contrast in the Mediterranean areas, where the grain filling stage is shorter, the harvests are characterized by lower yield but good protein content level. Many studies confirmed that the meteorological factors, such as air temperature (Pan *et al.*, 2006; Smith and Gooding, 1999) and rainfall, greatly affect the grains quantity. Nevertheless most of studies focus on common wheat and few works were performed on the impact of meteorological variables on winter durum wheat (Peltonen-Sainio *et al.*, 2010).

The NDVI (*Normalized Difference Vegetation Index*) is a remote sensing index that supply a descriptive value of crop status being related to the vegetation cover density. The maximum NDVI value corresponds to the period of maximum photosynthetic activity due to highest rate of biomass production (Anderson, 1992). Maximum NDVI in wheat was recorded between the end of vegetative growth and the flowering start (Whan *et al.*, 1991); after the flowering and during the grain maturity stage, NDVI values decrease as a consequence of a photosynthetic activity reduction (Connor *et al.*, 1992). Many researches on durum wheat highlight a close relationship between NDVI and the product characteristics (i.e. yield and grain protein content) (Broge and Lebance, 2001). Nevertheless the most of these studies detected NDVI values through optical remote-sensing instruments at ground level, without evaluating the reliability of satellite measurements at large scale. The relationship between NDVI and wheat yields or biomass is confirmed by many authors (Raun *et al.*, 1993; Labus *et al.*, 2002; Hansen *et al.*, 2002). On the other hand the scientific literature shows controversial results about NDVI predictive role for grain protein.

Hansen *et al*. (2002) evaluated NDVI as a predictor index of the common wheat harvests obtaining good performance for the yield, but unsatisfactory results for grain protein content. Similarly, Freeman *et al*. (2003) reported that NDVI provided a trusted estimate of durum wheat yield and nitrogen uptake by the epigean biomass, but no significant correlations were found with grain protein content. Therefore for wheat the prediction of grain quality from remote sensing remains a challenge.

The current work studies the relationship between satellite-based NDVI, meteorological variables, recorded by ground weather stations, and the qualitative and quantitative aspects of winter durum wheat harvests, in a large scale study performed in Val d'Orcia. The main objective is the evaluation of the possible use of indices derived both by remote sensing and meteorological data to predict the crop performance, in terms of yield and qualitative characteristics.

MATERIALS AND METHODS

Study area

The research was carried out in Val d'Orcia (Province of Siena, Tuscany, Central of Italy) characterized by a typical Mediterranean climate with an average yearly air temperature of 13.6°C and yearly cumulated rainfall of about 715 mm, mainly concentrated during winter and autumn. Val d'Orcia, extended for 668.62 km² of which 15% cultivated with winter durum wheat, is one of the main area for the high quality production necessary for pasta industry. The Val d'Orcia area was studied, with the support of ArcGIS 9.1 software, through orthophotos, soils and land use maps, excluding the urban centers and identifying a study area of 135 km² characterized by the predominance of arable land and clay loam soil.

Meteorological indices

The meteorological data were acquired by five ground weather stations, located within the Val d'Orcia, in order to accurately represent the mean meteorological conditions over the study area. The sum of active temperatures above 0°C (SAT), equation (1), and the sum of precipitation (SP), equation (2), were calculated, considering the growing season of the crop from November to June, over the period 1998-2009.

$$SAT = \sum_{01/11}^{30/06} (t_{md} \geq 0) \qquad (1)$$

$$SP = \sum_{01/11}^{30/06} P_{mm} \qquad (2)$$

where t_{md} is the average daily air temperature (°C) and P_{mm} is the daily cumulated precipitation (mm).

Remote sensing reflectance index

Normalized Difference Vegetation Index (NDVI) data for the period 1998-2009 were supplied by raster images freely available on website (www.free.vgt.vito.be). The images, with spatial resolution approximately 1 km x 1 km and processed with a time-step of 10-day, were acquired by the VEGETATION sensor (VGT) on board the SPOT satellite.

The images supply NDVI values, calculated following the equation (3) (Peñuelas and Filella, 1998) and computed to finally obtain maximum value composites (MVCs) on a 10-day basis (Holben, 1986).

With the support of ArcGIS 9.1 software a single NDVI value for each interval was calculated as the mean of all pixels within the study area.

$$NDVI = (R_{900} - R_{680}) / (R_{900} + R_{680}) \qquad (3)$$

where R_{900} is the reflectance in near infrared wavelength (900 nm) and R_{680} is the reflectance in red region (680 nm).

Productive variables

The qualitative and quantitative variables taken into account were: yield (Y), percentage of protein on grain dry matter (P), kernel specific weight (W) and total protein production (T), calculated as the percentage of P on Y.

Crop data were supplied by the Council for Research in Agriculture (CRA), by the Agricultural Consortium of Siena and by "Carletti" farm for a total of 20 farms placed in the study area.

The data series used for the analysis is represented by the mean of the grain protein content of the locations for the period 1999–2009. Wheat varieties used for this study had similar characteristics and no significant differences in grain protein content. During the period analyzed, nitrogen fertilization and crop management remained constant under the agreement between the farms and the Agricultural Consortium (fertilization plan: 160 kg/ha N, distributed in three times, and 90 kg/ha P_2O_5 at sowing).

Statistical analysis

Independent variables SP, SAT and NDVI and dependent variables Y, P, W and T were taken into account for the statistical analysis. The simple linear correlation between the meteorological indices and the dependent variables was calculated on a monthly and multi-monthly basis. In the same way, the correlation between NDVI and the dependent variables was calculated on a 10-day and multi 10-day basis taking into account the three monthly NDVI values related to first 10-day (I), second 10-day (II) and third 10-day (III). All possible combinations during the period November-June were investigated in order to identify the periods during which the meteorological variable show a significant effect on harvest and during which the NDVI is descriptive of the crop status.

Moreover two multi-regression analysis were carried-out, one taking into account all independent variables and one considering only the meteorological indices. The results were evaluated identifying for each month the independent variable or the combination of independent variables with higher predictive power on quality and quantity of harvest.

RESULTS

Grain protein content

P showed negative and positive correlation, respectively with SP and SAT. The single monthly SP was not significantly correlated, otherwise the multi-monthly analysis highlighted significant correlation, with highest *r* values for the periods November-May (r = -0.757) and November-April (r = -0.712) (Tab. 1). The single monthly SAT was correlated with P in April (r = 0.609) and the multi-monthly analysis showed correlations in the spring-early summer period involving the months from March to June, with highest r values in February-June (r = 0.684), January-June (r = 0.634) and February-May (r = 0.613) (Tab. 2). These results confirm the positive effect of temperature, mainly during the spring-summer months, on grain protein accumulation (Motzo *et al.*, 2007).

NDVI recorded from April to June was inversely correlated with P. The single 10-day analysis showed higher *r* value in the second 10-day of June and in the second half of May (r = -0.769); the early predictor period was found in the second 10-day of April (r = -0.667). The multi-10-day analysis indicated higher *r* value for the period from the second half of May to the second half of June (r = -0.798) (Tab. 3).

The multiple regression analysis indicated that the best predictive index of P was SP in the period from January to March. The multi-regression analysis showed SP and SAT as the best combination for the period April-June (Tab. 4).

Nov	Nov -Dec P_1	Nov -Jan P_1T_1	Nov -Feb P_2T_1	Nov -Mar P_1T_1	Nov -Apr P_2	Nov -May P_2	Nov -Jun P_1
Dec T_1	Dec -Jan Y_1T_2	Dec -Feb P_1T_2	Dec -Mar P_1T_1	Dec -Apr P_1T_1	Dec -May P_1	Dec -Jun	
Jan T_1	Jan -Feb	Jan -Mar	Jan -Apr	Jan -May	Jan -Jun		
Feb	Feb -Mar	Feb -Apr	Feb -May	Feb -Jun			
Mar	Mar -Apr	Mar -May	Mar -Jun				
Apr	Apr -May	Apr -Jun					
May	May -Jun						
Jun							

Tab. 1 - Correlations, calculated on a monthly and multi-monthly basis, between sum of precipitation and harvest characteristics. Legend: P = protein percentage; W = specific weight; Y = yield; T = total protein; significance: $_1$ = $P \leq 0.05$; $_2$ = $P \leq 0.01$; $_3$ = $P \leq 0.001$; the positive correlations are highlighted in bold.

Tab. 1 - Correlazioni, calcolate su base mensile e multi-mensile, tra la somma delle precipitazioni e le caratteristiche del raccolto. Legenda: P = percentuale di proteine; W = peso specifico; Y = resa; T = proteine totali; significatività: $_1$ = $P \leq 0.05$; $_2$ = $P \leq 0.01$; $_3$ = $P \leq 0.001$; le correlazioni positive sono evidenziate in grassetto.

Kernel specific weight

There was not significant correlation between W and SP (Tab. 1), while the results showed negative correlation with SAT. The effect of temperature is evident during all crop cycle and since the early stages: higher *r* values were recorded in March-May (*r* = -0.924) and the early predictor period was December-March (*r* = -0.617) (Tab. 2). The results highlighted positive correlation between NDVI and W since April. On 10-day basis, the most significant correlation occurred in the second half of May (*r* = 0.757) as the multi 10-day analysis confirmed higher *r* value for the period 11 May -30 May (*r* = 0.791) (Tab. 3).

The multiple regression analysis indicated SAT as the earlier predictive index of W in March and the multi-regression between SP and SAT in April, May and June (Tab. 4).

Yield

The rainfall did not show significant effects on Y, while negative correlation was recorded with SAT during the most of growing cycle: higher *r* values were observed in May (*r* = -0.839) and in March-May (*r* = -0.820) (Tab. 2). Positive correlations were found between NDVI and Y in April, May and June: on 10-day basis, higher *r* values occurred in the second half of May (*r* = 0.636) and, on multi-10-day basis, in the periods 21 April to 10 June and (*r* = 0.733) from 21 to 30 May (*r* = 0.724) (Tab. 3). These results are supported by others studies that showed positive correlation between Y and plant biomass at flowering (Whan *et al.*, 1991; Anderson, 1992). The multiple regression analysis indicated SP and SAT as the best predictor of Y, highlighting the relevance of winter rainfall and spring temperatures (Tab. 4).

Total protein production

Negative correlations between SP and T were found with high significant values in December-January (*r* = -0.803) and December-February (*r*= -0.736) (Tab. 1). Negative correlations were found also between STA and T with highly

significant values in May (r = -0.685) and in March-May (r = -0.587) (Tab. 2). NDVI showed negative correlation with T only in the second half of November (r = -0.636).
The multiple regression analysis indicated SP as the best predictor of T in March and April, and for the following months of May and June the multi-regression between SP and SAT, confirming the role of winter rainfall and spring temperatures.

DISCUSSION AND CONCLUSIONS

The best prediction of the productive variables was performed through the combined use of meteorological indices, nevertheless NDVI was able singularly to give predictive information on the quality and quantity of winter durum wheat harvest.
P resulted negatively correlated with winter precipitation and positively correlated with spring temperatures. W and Y were not significantly correlated with rainfall, but significant and negative correlations were found with spring temperatures. The NDVI was in agreement with the rainfall effect showing a negative correlation with P. On the other hand, NDVI and temperature had respectively positive and negative relationship with W and Y values.
Studies can explain the negative effect of rainfall on P: precipitation encourages the dilution of early nitrogen reserves by vegetative proliferation, it increases the leaching and other forms of soil nitrogen loss, it may augment soil moisture reserves so that leaf life is extended during grain growth favoring carbohydrate assimilation and translocation more than that of nitrogen (Smith and Gooding, 1999). Therefore NDVI, as index of the vegetation cover, probably was able to describe the N dilution effect that occurs corresponding to plant vegetative proliferation.
Temperature had a positive effect on growth, accelerating the cycle and then decreasing the grain filling duration (Wheeler *et al.*, 1996). The final grain size, and hence the dilution degree of accumulated nitrogen, is closely related to the length of time the crop stay green after flowering: higher temperatures shorten this period penalizing the total carbohydrate accumulation and furthering the protein concentration (Smith and Gooding, 1999). Furthermore with a higher temperature range, from emergency to earing stage, the fruit setting improves with higher number of ears and, therefore higher number of seeds characterized by smaller size and lower specific weight. Moreover, the temperature plays an important role on the water status of the plant increasing

	Nov - Dec	*Nov - Jan*	*Nov - Feb*	*Nov - Mar*	*Nov - Apr* W_1	*Nov - May* W_2Y_1	*Nov - Jun* W_2Y_1
Dec	*Dec - Jan*	*Dec - Feb*	*Dec - Mar* W_1	*Dec - Apr* W_1	*Dec - May* W_2Y_1	*Dec - Jun* W_3Y_1	
Jan	*Jan - Feb*	*Jan - Mar* W_1	*Jan - Apr* W_1	*Jan - May* W_2	*Jan - Jun* $P_1W_3Y_1$		
Feb	*Feb - Mar* W_1	*Feb - Apr* W_1	*Feb - May* **P_1**W_3	*Feb - Jun* **P_1**W_3			
Mar W_2	*Mar - Apr* **P_1**W_2	*Mar - May* $W_3Y_2T_1$	*Mar - Jun* **P_1**W_3Y_2				
Apr **P_1**	*Apr - May* **P_1**W_2Y_2	*Apr - Jun* W_1Y_1					
May $W_2Y_3T_1$	*May - Jun* W_1Y_1						
Jun							

Tab. 2 - Correlations, calculated on a monthly and multi-monthly basis, between SAT (sum of active temperature) and harvest characteristics. Legend: P = protein percentage; W = specific weight; Y = yield; T = total protein; significance: $_1$ = $P \leq 0.05$; $_2$ = $P \leq 0.01$; $_3$ = $P \leq 0.001$; the positive correlations are highlighted in bold.
Tab. 2 - Correlazioni, calcolate su base mensile e multi-mensile, tra SAT (somma delle temperature attive) e le caratteristiche del raccolto. Legenda: P = percentuale di proteine; W = peso specifico; Y = resa; T = proteine totali; significatività: $_1$ = P≤0.05; $_2$ = P≤0.01; $_3$ = P≤0.001; le correlazioni positive sono evidenziate in grassetto.

AprI	*AprI-AprII*	*AprI-AprIII*	*AprI-MayI*	*AprI-MayII*	*AprI-MayIII*	*AprI-JunI*	*AprI-JunII*	*AprI-JunIII*
							$\mathbf{Y}_1$	$\mathbf{W}_1\mathbf{Y}_1$
AprII	*AprII-AprIII*	*AprII-MayI*	*AprII-MayII*	*AprII-MayIII*	*AprII-JunI*	*AprII-JunII*	*AprII-JunIII*	
$\mathbf{P}_1$					$\mathbf{W}_1\mathbf{Y}_1$	$P_1\mathbf{W}_2\mathbf{Y}_1$	$P_1\mathbf{W}_1\mathbf{Y}_1$	
AprIII	*AprIII-MayI*	*AprIII-MayII*	*AprIII-MayIII*	*AprIII-JunI*	*AprIII-JunII*	*AprIII-JunIII*		
			$\mathbf{W}_2\mathbf{Y}_1$	$\mathbf{W}_1\mathbf{Y}_2$	$P_1\mathbf{W}_2\mathbf{Y}_1$	$P_2\mathbf{W}_2\mathbf{Y}_1$		
MayI	*MayI-MayII*	*MayI-MayIII*	*MayI-JunI*	*MayI-JunII*	*MayI-JunIII*			
	$\mathbf{W}_1$	$\mathbf{W}_2\mathbf{Y}_1$	$P_1\mathbf{W}_1\mathbf{Y}_1$	$P_2\mathbf{W}_1\mathbf{Y}_1$	$P_2\mathbf{W}_1\mathbf{Y}_1$			
MayII	*MayII-MayIII*	*MayII-JunI*	*MayII-JunII*	*MayII-JunIII*				
	$P_1\mathbf{W}_2\mathbf{Y}_2$	$P_2\mathbf{Y}_1$	$P_2\mathbf{W}_1\mathbf{Y}_1$	$P_2\mathbf{W}_1\mathbf{Y}_1$				
MayIII	*MayIII-JunI*	*MayIII-JunII*	*MayIII-JunIII*					
$P_2\mathbf{W}_2\mathbf{Y}_1$	P_2	$P_1\mathbf{W}_1\mathbf{Y}_1$	$P_2\mathbf{W}_1\mathbf{Y}_1$					
JunI	*JunI-JunII*	*JunI-JunIII*						
P_1	P_2	P_2						
JunII	*JunII-JunIII*							
$P_2\mathbf{W}_1$	$P_2\mathbf{W}_1$							
JunIII								
$P_1\mathbf{Y}_1$								

Tab. 3 - Correlations, calculated on a 10-day and multi 10-day basis, between NDVI and the quali-quantitative variables of harvest. Legend: I = first 10-day of month; II = second 10-day of month; III = third 10-day of month; P = protein percentage; W = specific weight; Y = yield; T = total protein; significance: $_1$ = $P \leq 0.05$; $_2$ = $P \leq 0.01$; $_3$ = $P \leq 0.001$; the positive correlations are highlighted in bold.
Tab. 3 - Correlazioni, calcolate per decadi e per valori medi di più decadi, tra NDVI e le variabili quali-quantitative del raccolto. Legenda: I = prima decade del mese; II = seconda decade del mese; III = terza decade del mese; P = percentuale di proteine; W = peso specifico; Y = resa; T = proteine totali; significatività: $_1$ = $P \leq 0.05$; $_2$ = $P \leq 0.01$; $_3$ = $P \leq 0.001$; le correlazioni positive sono evidenziate in grassetto.

the transpiration rate and reducing the potential yield (Simane *et al.*, 1993).
T is negatively correlated with winter precipitation and spring temperatures, depending on both productive variables P and Y. These results indicate that the weather predominant effects consist of the negative impact of rainfall on P and of temperature on Y.
The empirical approach is a limitation to the extension of the study results to other climatic contexts. However, the acquired knowledge can be useful for the modeling applications integrated with the climatic seasonal forecast, in order to develop a winter durum wheat local forecast system able to supply information about the potential quality and quantity of harvest to cereal growers, technicians and pasta producers.

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Month			r	S
November	P	SP_{nov}	-0.51	n.s.
	W	$NDVI_{novIII}$	-0.45	n.s.
	Y	$NDVI_{novIII}$	-0.59	n.s.
	T	$NDVI_{novIII}$	-0.64	*
December	P	$SP_{nov-dec}$	-0.59	n.s.
	W	$NDVI_{decI}$	-0.58	n.s.
	Y	$NDVI_{novIII}$	-0.59	n.s.
	T	SP_{dec}	-0.67	*
January	P	$SP_{nov-jan}$	-0.65	*
	W	$NDVI_{decI}$	-0.58	n.s.
	Y	$SP_{dec-jan}$	-0.59	n.s.
	T	$SP_{dec-jan}$	-0.80	**
February	P	$SP_{nov-feb}$	-0.71	*
	W	$NDVI_{decI}$	-0.58	n.s.
	Y	$SP_{dec-jan}$	-0.59	n.s.
	T	$SP_{dec-jan}$	-0.80	**
March	P	$SP_{nov-feb}$	-0.71	*
	W	SAT_{mar}	-0.75	**
	Y	$SP_{dec-jan}SAT_{mar}$	0.83	**
	T	$SP_{dec-jan}$	-0.80	**
April	P	$SP_{nov-apr}SAT_{apr}$	0.83	**
	W	$SP_{mar-apr}SAT_{mar-apr}$	0.88	**
	Y	$SP_{dec-jan}SAT_{mar-apr}$	0.91	***
	T	$SP_{dec-jan}$	-0.80	**
May	P	$SP_{nov-may}SAT_{feb-may}$	0.94	***
	W	$SP_{mar-apr}SAT_{mar-may}$	0.97	***
	Y	$SP_{dec-jan}SAT_{mar-may}$	0.94	***
	T	$SP_{dec-jan}SAT_{mar-may}$	0.93	***
June	P	$SP_{nov-may}SAT_{feb-may}$	0.94	***
	W	$SP_{mar-apr}SAT_{mar-may}$	0.97	***
	Y	$SP_{dec-jan}SAT_{mar-may}$	0.94	***
	T	$SP_{dec-jan}SAT_{mar-may}$	0.93	***

Tab. 4 - Best predictive indices in each month for quali-quantitative variables of winter durum wheat harvest. Legend: decI = first 10-day of month; decII = second 10-day of month; decIII = third 10-day of month; P = protein percentage; W = specific weight; Y = yield; T = total protein; r = coefficient of correlation; S = significance; n.s. = not significant; * = $P \le 0.05$; ** = $P \le 0.01$; *** = $P \le 0.001$.

*Tab. 4 - I migliori indici predittivi in ciascun mese per le variabili quali-quantitative del raccolto del frumento duro . Legenda: decI = prima decade del mese; decII = seconda decade del mese; decIII = terza decade del mese; P = percentuale di proteine; W = peso specifico; Y = resa; T = proteine totali; r = coefficiente di correlazione; S = significatività; n.s. = non significativo; * = P≤0.05; ** = P≤0.01; *** = P≤0.001.*

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