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Prediction of potential and attainable yield of wheat : A case study on yield gap

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सार - इस शोध पत्र में गेहूँ की फसल की उपज की और अधिक बढ़ोतरी के लिए खेत पर आधारित प्रयोग और खेती करने की प्रणाली के अनुकरण की भूमिका के विषय में चर्चा की गई है और यह पता लगाया गया है कि संभावित उत्पादकता की जानकारी से उत्पादन प्रणाली की क्षमता में किस प्रकार सुधार लाया जा सकता है। जब फसल मौसम अनुकरण निदर्शों में खेत पर आधारित प्रयोगों से प्राप्त हुई जानकारी का उपयोग किया जाता है तो जिस पर्यावरण में फसल उगाई जा रही है उसमें प्राप्त होने वाली वास्तविक पैदावार और संभावित पैदावार दोनों के मध्य अंतर निर्धारित किए जा सकते हैं तथा पैदावार में वृद्धि के अवसरों का मूल्यांकन किया जा सकता है। इनसे प्राप्त हुए परिणामों से यह पता चलता है कि जब क्षेत्र की वास्तविक औसत पैदावार में वृद्धि की प्रवृति पाई जाती है तब संभावित और प्राप्त हुई पैदावार में ह्रास की प्रवति पाई जाती है। जब समयानुसार सकल और प्रबंधन उपज के मध्य अंतर में कमी होती है तब अनुसंधान पैदावार के दौरान की उपज में किसी प्रकार की प्रवृति का पता नहीं चलता है। यह लगभग अस्सी के दशक के पूर्वार्द्ध से नब्बे के दशक के उत्तरार्द्ध तक की स्थिति है। कृषि जलवायु क्षेत्र की संभावित विभिन्न वार्षिक पैदावारों के मध्य अंतर को निर्धारित करने के लिए अनुकरण निदर्शों के लाभों के बारे में इस अध्ययन में बताया गया है।

ABSTRACT. This study reports the role of field experimentation and system simulation in better quantifying the productivity of wheat crop, and examine how knowledge on potential productivity can improve the efficiency of the production system. When knowledge from field experimentation is utilised into crop weather simulation models, gap between actual, attainable and potential yield for a given environment can be determined and opportunities for yield improvement can be assessed. Results show that while actual district average yields show increasing trend, decreasing trend is noticed in potential and attainable yield. While the total and management yield gap is decreasing over time, research yield gap does not show any trend, it is nearly stagnant from early eighties to late nineties. The study reported here presents the advantage of simulation models to determine the yield gap against a variable annual yield potential for a agro-climatic region.

Key words – Potential production, System simulation, Management, Yield gap.

1. Introduction

The rate of annual growth of wheat production and yield showed a peak during green revolution in India, but in eastern Uttar Pradesh region the yield gap between farmer's and experimental field was quite significant. The average yield in experimental trial was around 5.5 t/ha but the average/ha productivity of east UP is only 2.2 t/ha. This region alone account for 3 mha under wheat and it is a clear indication of the extent of under harvested yield that is still available in this region. Wheat productivity may be enhanced by minimising "Research yield gap" (Potential yield–Experimental or attainable yield) and "Management yield gap" (Attainable yield–Actual yield) through improving efficiency of present agricultural system and stabilising the productivity level with appropriate management practices.

A practical, action oriented distinction between different production levels has been proposed by Rabbinge(1993).He distinguished the following categories

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(*i*) *Potential yield* : growth in condition with ample soil water and nutrients and without any physical or biological stress on the crop plants. Radiation, temperature, CO_2-level, crop characteristics are the yield defining factors. Modelling potential yield requires particularly the understanding of crop physiology and agrometeorology.

(*ii*) *Attainable yield* : 50-20% below the potential yields; the reduction is caused by limiting factors such as water, nitrogen or phosphorus. Such limitation can largely be avoided by yield increasing measures (fertilizer, irrigation). Best farms attain this yield level. Soil physics and soil chemistry is important disciplines in the study of attainable yield.

(*iii*) *Actual yield* : roughly 50-0% below the attainable yield due to reducing factors, such as weeds, pests/disease and pollutants. Yield reduction can be avoided by crop protection measures such as integrated pest management. This situation is very common in many of the world's agricultural crops.

System analysis and crop growth simulation are relatively recent techniques that offer a means of quantitative understanding of effects of natural and management factors on crop growth and productivity. Models help in the study of the systems, in particular where real life experimentation would be either impossible, or inordinately expansive. It also permits the study of long-term effects since the time horizon over which the model is run is within the control of the user. Wheat crop modelling has been done in India (Aggarwal and Kalra, 1994; Rathore *et al*., 1994; Aggarwal *et al*., 2000; Sankaran *et al*., 2000, Mall *et al*., 2001) and other part of the world (Bell and Fischer, 1994; Chipanshi *et al*., 1997; Ewert *et al*., 1999) to quantify the growth response characteristics to various management factors.

The objective of this paper is to (*i*) calibrate and validate two crop growth simulation models WTGROWS and CERES-wheat, and (*ii*) their applications to determine potential wheat yields, attainable yield and yield gaps in Varanasi districts of eastern Uttar Pradesh.

2. Materials and methods

2.1. *Study site and climate description*

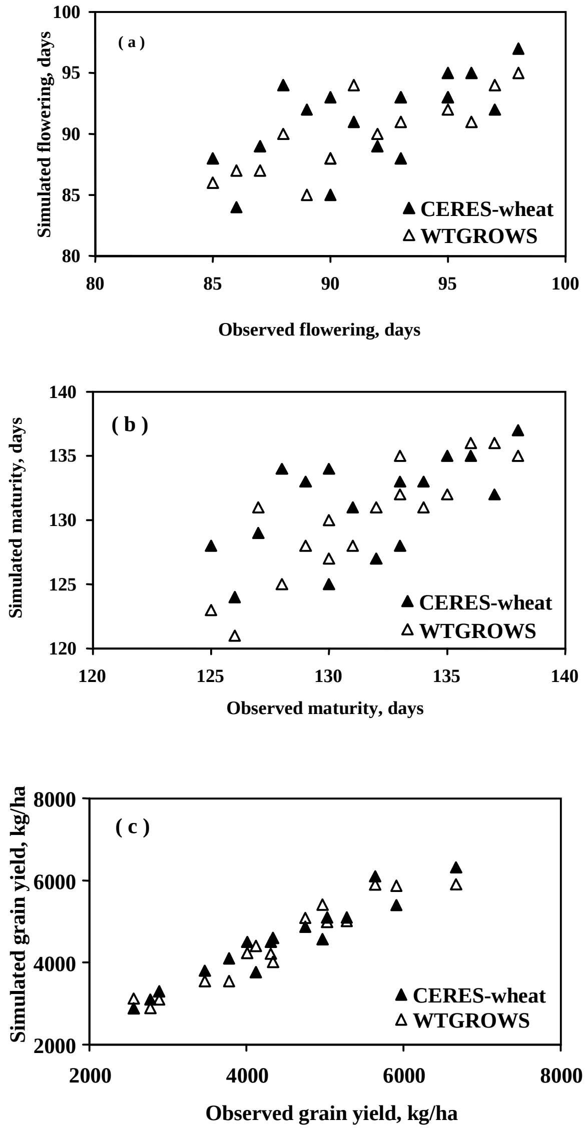
Varanasi district is situated in the Indo-gangetic plain of India at an elevation of 75 meters above mean sea level and 25° 20´ latitude and 83° 03´ longitude having subtropical climate. The mean annual rainfall is about 1056 mm/year (± 172 SD) and the estimated annual potential evapotranspiration (PET) is approximately 1525 mm/year (Rao *et al*., 1971). The percentage distribution of annual rainfall is 88 percent from June to September (monsoon season) and 7.7 percent from October to February (winter season) 4.3 percent from March to May (summer season). The temperature begins to rise from February and reaches maximum by the end of May or early June. The average mean maximum temperature is 39.4° C during May-June. The coldest period of the year is in between the last week of December and first week of January. The average minimum temperature during December-January is 9.3° C. Wheat are planted in this region during November-December and harvested in April to May. The soil of this area is alluvial in origin. The majority of soils in six-category system of USDA soil Taxonomy *i.e*. group Ustochrepts and other belongs to group Ustifluvents (Singh *et al*., 1989).

2.2. *Field experiment*

The crop data were obtained from information collected during field experiments on a long-term varietal trial of wheat crop conducted at Regional Agriculture Experiment and Demonstration centre, during 1989-90 to 1996-97. Wheat variety HUW206, was raised in a randomised block design with three replications under irrigated condition on sandy clay loam soil. This high yielding variety is presently growing in eastern Uttar Pradesh region. The soil of this area is alluvial in origin. The crop was sown at 2 sowing dates 15 November and 15 December during 1989-90 to 1996-97. The crop was irrigated (50 mm / irrigation) at 20,40,60,80 and 90/100 days after sowing. The crop was sown in rows 20 cm apart at a seeding rate of 100 kg/ha. The crop observations at various phenological stages of growth were utilised in the present investigation. Fertiliser was applied at the rate of 120 kg N (1/2 basal and ½ at crown root initiation stage), 60 kg P, 40 kg K per hectare.

2.3. *The models*

CERES-Wheat (Crop Estimation through Environment Resource Synthesis wheat) is a process oriented management level model, which has the capability to simulate growth, development and yield of wheat genotypes under divers environments (Ritchie and Otter 1985). The model has a balanced approach in terms of its emphasis on the biophysics of crop growth and development, including weather effects on phenology and water and nitrogen stresses on general growth. The major components of the model are the vegetative and reproductive development, carbon balance, water balance and nitrogen balance modules which relate the flow the mass and information between different modules. However, it does not simulate impact of phosphorous, weeds; and pest and diseases on growth and assumes that they are taken care of by management practices.



Figs. 1(a-c). Comparison of simulated and observed (a) flowering duration, (b) maturity duration and (c) grain yields

A mechanistic crop growth simulation model – WTGROWS (Wheat Growth Simulator)- was developed to evaluate the effects of climatic variables, genotype, agronomic management, and water and nitrogen availability on crop growth, development, water and nitrogen use, and productivity of wheat in tropical and subtropical environments (Aggarwal *et al*., 1994). The model simulates daily dry matter production as a function of irradiance, maximum and minimum temperatures and water and nitrogen stresses. Crop aspects of the model are arranged in submodels covering development, photosynthesis, respiration, carbohydrate partitioning, dry matter production, leaf area, grain growth and transpiration. A soil water balance model is attached to simulate water uptake and to determine water stress. Another submodel determines nitrogen uptake, distribution and nitrogen stress. Detailed descriptions of the model are given in Aggarwal *et al*. (1994).

2.4. *Data used*

Both models require input data on soil, crop and weather for its calibration in different environments. Weather (Radiation, maximum and minimum temperatures and rainfall) and soil (albedo, first stage evaporation, drainage, USDA Soil Conservation Service Curve Number for runoff and layerwise information and saturation, field capacity, wilting point, texture and hydraulic conductivity) and crop management data (Dates of sowing, plant and row spacing, irrigation, fertiliser etc.) were collected for the location under study.

Daily weather data from 1980 to 1999 were used in study collected from agro-meteorological observatory, Banaras Hindu University, Varanasi. Observed district wheat grain yield (1980-81 to 1998-99) for the study site was obtained from statistical magazine, Varanasi and Krishi Bhawan, Lucknow, Uttar Pradesh.

2.5. *Model calibration*

In order to evaluate the performance of CERES-wheat model to the eastern Uttar Pradesh region of Indo-gangetic plain, calibration of the model was required. The model requires seven cultivar specific genetic coefficients. These genetic coefficients for growth and development were derived following Hunt's Method (Hunt *et al*., 1993). Minimum crop data sets required are dates of sowing, flowering and maturity, grain yield, biomass, grain/m^2, per grain weight. Four of the genetic coefficients, PHINT, P1V, P1D and P5 are related to development aspects, and the remaining three describing growth and grain development, G1, G2 and G3. The model was calibrated using the observed field experiment data of 1996-97 season experiment. The Published values of genetic coefficients (Hundal and Kaur, 1997) were used for initial model run. Each of the genetic coefficients was interactively increased/decreased from the given value and the predicted values of the relevant growth and yield parameter were compared with the observed values. Then those values of the coefficients, which most realistically simulated the growth, and yield of wheat were selected.

WTGROWS model is well calibrated in India by Aggarwal *et al*. (1994). Only thermal time for anthesis to maturity (TTVG = 995^{o} C day) and potential grain weight (POTGWT = 45 mg grain^{-1}) was modified in the model.

TABLE 1

Actual, potential, attainable wheat yields and yield gap at Varanasi district

Sowing year	Actual district yield	Potential yield		Attainable yield	
		WTGROWS	CERES-wheat	WTGROWS	CERES-wheat
1980	1369	7146	7270	5742	6042
1981	1544	6988	7376	5867	6167
1982	1443	7183	7267	5269	5569
1983	1727	6466	6893	5927	6227
1984	1549	7436	7114	5212	5512
1985	1711	7091	7390	5041	5341
1986	1648	6532	6491	5042	5678
1987	1936	6541	6913	4789	4648
1988	1949	6524	6910	5054	5354
1989	1871	6301	6758	5549	5849
1990	2021	7260	6894	5401	5701
1991	2575	6508	6419	4913	5213
1992	2252	7466	7089	4812	5112
1993	2550	6872	6681	5253	5553
1994	2344	6643	6252	4789	4791
1995	2259	6571	6379	5556	5856
1996	2740	6337	6771	5083	5383
1997	2884	6479	6823	5432	5345
1998	2183	6654	6879	5564	5765
Average	2029	6789	6872	5278	5531

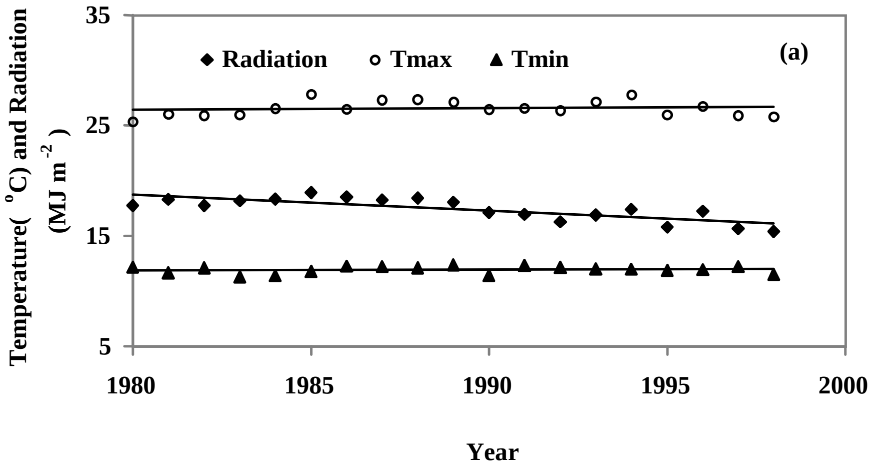
3. Results and discussions

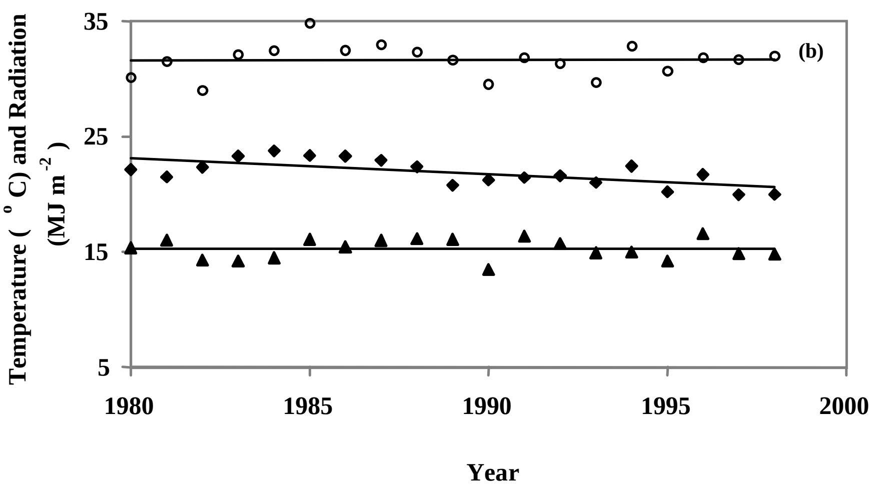
3.1. *Model validation*

The prediction of flowering and maturity date is very important for the success of simulation models. Observed flowering duration varied from 85 to 95 days whereas simulated duration ranged from 84 to 97 days for CERES-wheat model and 85 to 95 days for WTGROWS model. Results showed that both models were able to simulate flowering duration reasonably well for most treatments Fig. 1(a). Relatively, WTGROWS model simulated flowering duration with less error [Root Mean Square Error (RMSE) = 2.5] than CERES-wheat (RMSE=3.2). Nevertheless, most of the simulated values were within 15% error lines for both models except in 3-4 treatments where the simulated values had larger error. The physiological maturity dates simulated by the both models corresponded quit well with that accurately observed in the field experiments Fig. 1(b).

Fig. 1(c) shows a close correspondence between simulated and observed grain yields across all experiments for both models. Observed grain yields ranged from 2567 kg ha^{-1} to 6670 kg ha^{-1} depending upon the location whereas simulated grain yields ranged from 2879 kg ha^{-1} to 6317 kg ha^{-1}. It is evident from the figure that both models predicted grain yields within 15% of the measured yields except where the measured yields were lower than 3000 kg ha^{-1} indicating their inability to simulate crop growth when there is extreme stress. Relatively, WTGROWS simulated yields were closer to the observed values (RMSE=316 kg ha^{-1}) than CERES-wheat (RMSE=698 kg ha^{-1}).

The study reported here does not include the yield losses due to weeds, insects and diseases. The overestimation of grain yield by the model reflects the need for inclusion of losses due to pest and disease and closer examination of quantitative relationship governing the partitioning of photosynthesis in to biomass and grain yield. Both models simulated the trends in grain yield and phenology as measured in field experiments. There were, however, deviations as large as 15% in some cases, it can be concluded that both models performing satisfactorily and are adequate to simulate the potential yield and attainable yield.





Figs. 2(a&b). Maximum (T_{max}, °C) and minimum (T_{min}, °C) temperature and solar radiation(MJm $^{-2}$) during (a) crop season, (b) march month over Varanasi for last 19 years

3.2. *Trend of actual and predicted potential and attainable wheat yields*

The potential and attainable yields of the study site for the 1980-98 (year of sowing) period as influenced by weather were predicted using the CERES and WTGROWS models. CERES simulations were run, for 15 November sowing dates for each year. The average potential and attainable yields predicted by CERES were 6872 and 5542 kg/ha at 10% moisture, respectively, accord with local experience (Table 1). The average potential and attainable yields from the WTGROWS model, which assumes 15 November sowing, were 6789 and 5278 kg/ha respectively.

Linear regression of actual district yields indicates that the average yield has increased from 1980 to 1998 (sowing year) at a rate of 71.5 $kg^{-1}ha^{-1}y^{-1}$ (r^2 = 0.79) (Table 1). However, considerable variation in annual yield was apparent and more gain in yield after 1989 was observed. The observed year to year variation would presumably due to a combination of fluctuating weather conditions and fluctuation in the degree to which farmer's agronomic practices are optimised each year. Also the varieties changed throughout the period and while the general trend seen in other experiments is for yield of more recent varieties to exceed that of ones they replace, abrupt variety change will also contribute to year-to-year fluctuations in yield.

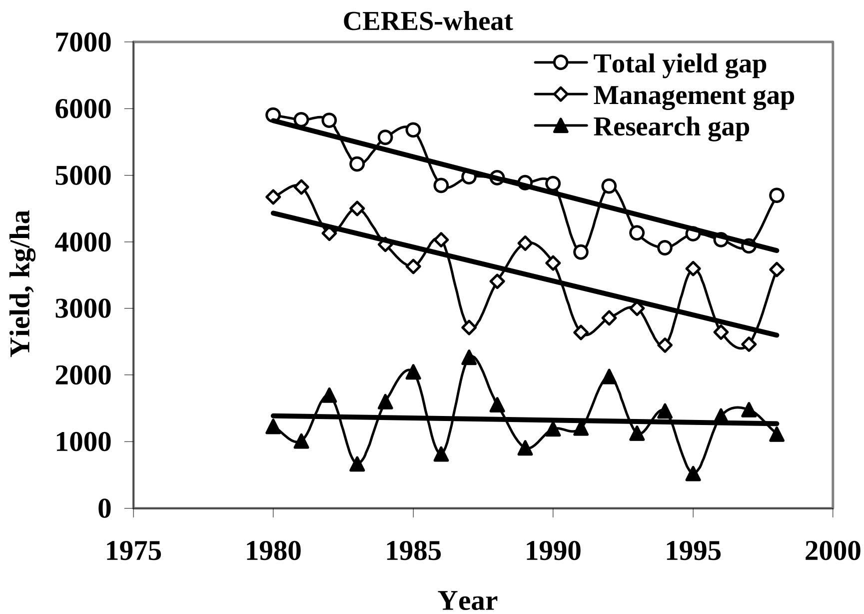


Fig. 3. Yield gap of wheat at Varanasi district

While the actual average annual yields increase modestly over time, potential yields predicted by the CERES and WTGROWS models showed also little decreasing trend of the order of 36.6 (R^2= 0.38) and 26.6 (R^2 = 0.15) kg^{-1} ha^{-1} y^{-1} respectively (Table 1). The variation in predicted potential yields across years highlights the act of complicating effect that changes in weather (Fig. 2) would have on analyse the trends in observed yields. Attainable yields predicted by the CERES and WTGROWS models showed also little decreasing trend of the order of 27.3 (R^2= 0.13) and 17.5 (R^2 = 0.07) kg^{-1} ha^{-1} y^{-1}, respectively (Table 1). A decline or stagnant of cereal yields in experimental fields including wheat in north India is now been noticed. Several reasons, in particular declining soil health and decreasing input use efficiency, have been proposed as the major reason for decline (Aggarwal *et al*., 2000; Sinha *et al*., 1998). The simulated decline in potential yields indicates that the observed yield decline in experimental yield could also be partly due to factors other than soil health (potential yields simulations assume there is no soil and management constraints, only crop physiology and its interaction with temperature and radiation are critical). The decreasing trend in potential and attainable wheat yields owing due to decreasing trend of solar radiation causing lower net-photosynthesis and dry matter production for the crop.

The deviation in solar radiation, especially during vegetative phase and grain filling was more crucial to the wheat crop. Solar radiation during wheat growing season and during grain filling duration showed marginally decreasing trend of the order of 0.14 (R^2= 0.56) and 0.13 (R^2 = 0.38) kg^{-1} ha^{-1} y^{-1} respectively (Fig. 1). The solar radiation used in the present study is derived from sunshine duration using Angstrom formula.

3.3. *Yield gap analysis*

It is observed that both models showed same type of trend during the study years. So for yield gap analysis, yield prediction by CERES-rice model has been used. Simulation models have often been used to understand the magnitude of yield gap and its principal causes in several studies. Fig. 3 shows the variation in total yield gap (potential-actual district average yield), management gap (attainable-actual district average yield) and research yield gap (potential-simulated attainable or observed experimental yields) over the years. Total yield gap and management yield gap are declining modestly over time, at the rate of 108.2 (R^2= 0.75) and 98.9 (R^2 = 0.58) kg^{-1} ha^{-1} y^{-1}, respectively over the years. The gap still exists due to late sowing, improper fertiliser and water management, variety used and pest losses. Wheat is often sown late (*i.e*. in December) in this region which causes significant reduction in grain yield. The total yield gap and management gap narrowed down from almost 6000 kg/ha in 1980 to less than 4000 kg/ha in late nineties. Aggarwal *et al*. (1994) suggested that a large part of yield gap is due to late planting and sub-optimal application of inputs.

While the total and management yield gap decrease modestly over time, research yield gap showed very little decreasing trend of the order of 9.2 (R^2=0.01) $kg^{-1}ha^{-1}y^{-1}$. The research gap is stagnant over the year, it was almost 1200 kg/ha in 1980 to more than 1100 kg/ha in late nineties (Fig. 3). The variation in research gap across years highlights the act of complicating effect that changes in weather. It is needed to narrow down the gap between maximum possible yield and attainable yield in this region by the researcher and planners.

4. Conclusions

The following conclusion may be made based on the present study.

(*i*) Although actual district average yield show increasing trend, decreasing trend is noticed in potential and attainable yield.

(*ii*) The total and management yield gap is decreasing over time.

(*iii*) The research yield gap does not show any trend, it is nearly stagnant from early eighties to late nineties.

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