POTATO POTENTIAL YIELD BASED ON CLIMATIC ELEMENTS AND CULTIVAR CHARACTERISTICS (1)

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ABSTRACT

There is currently a great deal of interest in estimating crop productivity as a function of climatic elements by means of different crop weather models. An agrometeorological model is presented based on carbon dioxide assimilation maximum rates for C_3 plants, fraction of photosynthetically active radiation, air temperature, photoperiod duration, and crop parameters under tropical climate conditions. Such crop parameters include leaf area and harvest indexes, dry matter content of potato tubers, and crop cycles to estimate potato potential yields. Field data from observed productivity obtained with the cultivar Itararé (IAC-5986), grown under adequate soil water supply conditions at four different regions in the State of São Paulo (Itararé, Piracicaba, Tatuí, and São Manuel), Brazil, were used to test the model. The results revealed an excellent performance of the agrometeorological model in study, with an underestimation of irrigated potato productivity less than 10%.

Key words: modelling, *Solanum tuberosum L.*, climatic elements, crop indexes, yield.

PRODUÇÃO POTENCIAL DA BATATEIRA EM FUNÇÃO DE PARÂMETROS CLIMÁTICOS E FITOTÉCNICOS

RESUMO

Há um grande interesse em estudos de estimativa da produtividade de culturas agronômicas em função de elementos climáticos através do uso de diversos modelos agrometeorológicos. Neste estudo, empregou-se um modelo agrometeorológico com base em taxas máximas de assimilação de dióxido de carbono para plantas de metabolismo C_3, radiação fotossinteticamente ativa, temperatura do ar, comprimento do dia e parâmetros fitotécnicos, como índice de área foliar, índice de colheita, conteúdo de matéria seca dos tubérculos e duração do ciclo fenológico da cultura para estimar a produtividade potencial da batateira. Dados de campo obtidos a partir de produtividades observadas com a cultivar Itararé (IAC-5986), sob condições de suprimento adequado de água no solo para quatro localidades distintas do Estado de São Paulo (Itararé, Piracicaba, Tatuí e São Manuel), Brasil, foram utilizados para testar o modelo. Os resultados revelaram um excelente desempenho do modelo climático em estudo, com subestimativas de rendimento potencial inferiores a 10%.

Palavras-chave: modelagem, *Solanum tuberosum* L., elementos de clima, índices culturais, produção.

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1. INTRODUCTION

The potential yield is the maximum yield of a given species or cultivar possible achievable under the existing conditions of solar radiation flux density, with all the other environmental factors considered to be optimal. Therefore, the potential yield is determined by the biological properties of the cultivar and radiation resources available for utilization. This yield category practically expresses the solar radiation resources for cultivating a given genotype in yield units, whereas the commercial yield is the yield attainable under existing farm conditions that takes into account all the factors limiting the production process and the crop yield.

Meteorological factors directly influence crop potential productivities, regulating its transpiration, photosynthesis, and respiration processes in such a way as to control the growth and development of the plants throughout their physiological cycle at a given site. The interaction of the meteorological factors with the crop responses is rather complex. However, by means of studies on determination techniques for assessing physiological crop responses to environmental factors under field conditions it is possible to come up with mathematical models to estimate crop potential production as a function of meteorological variables with a good precision.

Several researches have been conducted aiming at quantifying the effects of the environment on growth, development and yield of many agronomic crops. Among the main environmental factors that strongly govern all physiological processes of the plants one should bear in mind global solar radiation flux density, air temperature, and available soil water content (COELHO and DALE, 1980).

Potato yield improvements might be obtained by increasing the net daily photosynthetically radiation (PAR) through higher solar irradiance or longer photoperiod (STUTTLE et al., 1996). The photoperiod duration doubles from December to June at 50°N, while PAR increases eightfold from 2.11 to 17.01 MJ m^{-2} day^{-1} due to higher elevation of the sun above the horizon with lengthening days. Gross carbohydrate production on standard clear days increases from 108 to 529 kg ha^{-1} day^{-1} at 50°N, whereas it remains at about 420 kg ha^{-1} day^{-1} year-round near the equator. Low solar irradiance is a yield constraint at 30 to 40°N in winter when potatoes are grown to escape the summer heat (HAVERKORT, 1990).

SARQUIS et al. (1996) stated that the magnitude of the effect of elevated temperatures on potato growth and final yield is determined by an intricate interaction between soil temperature, air temperature, solar radiation flux density, and photoperiod duration. Their data extended previous observations of reduction in photosynthesis rate under elevated temperatures. Under field conditions reduced dioxide carbon assimilation rate could not explain the yield reduction observed; the temperature effect on assimilation was not as dramatic as it was on growth or yield. Other workers have reported a severe reduction in the rate of assimilation at air temperatures above 30°C under controlled experimental conditions. In such cases, reductions in CO_2 assimilation rate were shown to correlate well with reductions in growth and yield (KU et al., 1977; MIDMORE and PRANGE, 1992). These contrasting results reveal the complexity of plant responses to the combined effects of water and temperature stress, which inevitably occur in association under field conditions (PEREIRA and SHOCK, 2006).

Knowledge of climatic requirements of potato and its physiological responses to the environment is extremely important to help growers produce high yields with good tuber quality under site-specific atmospheric conditions. Such knowledge aims to provide a scientific support to research programs related to crop weather modelling. The SUBSTOR-Potato model takes into consideration daily air temperature, photoperiod, intercepted solar radiation, soil water and nitrogen supply. The model simulated fresh tuber yields ranging from 4 t ha^{-1} to 56 t ha^{-1} due to differences in weather patterns, soils, cultivars, and management practices (BOWEN, 2003).

KADAJA and TOOMING (2004) proposed a relatively simple model POMOD to calculate potato yield, which permits generalization of the knowledge in different disciplines on the potato crop yield levels, using the measured physiological, ecological, agrometeorological, and agronomical parameters of the plant. The input variables of the model can be divided into four groups: daily meteorological information, annual information, parameters of location and cultivar. The first group includes global radiation, air temperature, and precipitation. The location is characterized by geographical latitude and hydrological parameters. As to the cultivar factor, the parameters of gross and net photosynthesis, the coefficients of growth and maintenance respiration, and albedo of the crop are also needed. Simulation models for potato growth and yield were proposed by many researchers all over the world and are widely described in the literature.

The LINTUL-POTATO simulation model (KOOMAN and HAVERKORT, 1995) establishes potential yield of a certain cultivar for a determined growing period and plant density, and is based on: incident photosynthetically active radiation (PAR), fraction of PAR intercepted by the crop, and radiation use efficiency to produce dry matter. Phenological crop development is driven by accumulated air temperature, while development stage determines dry matter partitioning and, through haulm growth, the pattern of intercepted PAR is defined. The potential yield established with this simulation model was used by CALDIZ and STRUIT (1999) to perform a preliminary yield gap analysis regarding actual and attainable potato yield in different areas of Argentina.

Similarly to the potential productivity estimation model described by VILLA NOVA et al. (2001) and employed by VILLA NOVA et al. (2005) for sugar cane, we tested the performance of a model based on studies of maximum rates of carbon dioxide assimilation for a C_3 crop species as a function of air temperature, a fraction of global solar radiation flux density (PAR), photoperiod duration and leaf area index to estimate the potential productivity of potato crop, cultivar Itararé (IAC-5986), grown under adequate soil water supply conditions at four distinct sites of the State of São Paulo (Itararé, Piracicaba, Tatuí, and São Manuel), Brazil. In order to assess the performance of the proposed mathematical model, the estimated values of tuber yield were compared to observed productivity data under irrigation conditions for the studied sites.

2. MATERIAL AND METHODS

The proposed model for the estimation of potato potential yield (EPY), expressed by equation 1, is based upon the preconception that the maximum rate of dioxide carbon assimilation by the plants for production of carbohydrate (CH_2O) is related to the active photosynthetically fraction of the solar spectrum (PAR) and air temperature:

$$EPY = 1.27*10^{-6}*CDA*LAI*GS*N*C(LAI)*C(T)*HI*100/DM \quad (1)$$

where CDA is the carbon dioxide assimilation rate ($\mu L\ cm^{-2}\ h^{-1}$), LAI is the maximum leaf area index, GS is the number of days of the crop growing season, N is the mean photoperiod or day length duration throughout of the crop growing season (hours), C(LAI) is the correction factor for leaf area index variation over time, C(T) is the correction factor for maintenance respiration, HI is the harvest index, and DM is the dry matter content of the potato tubers (%).

Making use of the Clausius-Clapeyron's equation with the masses of CO_2 equal to 44 g mol^{-1} and of CH_2O corresponding to 30 g mol^{-1}, and considering 1 μL of CO_2 at 15°C (288 K) and 1 atmosphere equal to 1.863 * 10^{-6} g CO_2, one can infer that the CH_2O/CO_2 ratio assumes a value of 1.27 *10^{-6} of g CH_2O/μL CO_2 (VILLA NOVA et al., 2001).

Applying the necessary corrections to the aforementioned equation in order to express the estimates of potato potential yield in tons per hectare per crop cycle, we have:

$$EPY = 1.27*10^{-4}*CDA*LAI*GS*N*C(LAI)*C(T)*HI*100/DM \quad (2)$$

Without considering HI, the product of the other terms of the equation 2 depicts the estimation of the total dry matter produced by the potato plants, including roots, leaves and shoots.

Plotted and interpolated values of CDA were obtained from a graph that shows the relation between air temperature and maximum rate of CO_2 assimilation for a C_3 crop species under controlled conditions (HEEMST, 1986) as a function of the ambient temperature (T) and photosynthetically active radiation (PAR). However, under field conditions where plants are subjected to fluctuating temperature conditions, there appears to be adaptation of the photosynthetic apparatus. Thus, such plotted and interpolated CDA data are to be mathematically described by the following equation (PENNING de VRIES et al., 1989):

$$CDA = CDA_{max} * \left[1 - e^{\frac{-0.5*PAR}{CDA_{max}}}\right] \quad (3)$$

where CDA_{max} is the carbon dioxide assimilation maximum rate of 48 $\mu L\ cm^{-2}\ h^{-1}$.

The photosynthetically active radiation (PAR), expressed in Joule $m^{-2}\ s^{-1}$, was calculated by the equation proposed by ASSUNÇÃO (1994) as a function of the global solar radiation flux density and insolation ratio:

$$PAR = \frac{Qg}{3600 * N} * \left[0.5 - 0.1 * n/N\right] \quad (4)$$

where Qg is the mean global solar radiation flux density throughout the crop growing season (Joule $m^{-2}\ day^{-1}$), N is the mean photoperiod during the crop cycle (hours), and n/N is the mean insolation ratio of the period.

The global solar radiation flux density (Qg) was estimated taking into account the mean values of *a* and *b* Angstrom's coefficients obtained by CERVELLINI et al. (1966) for the State of São Paulo, Brazil. The equation used for the sites where there were no radiometric measurements available for the current study was the following:

$$Qg = Qo\left[0.24 + 0.58 * n/N\right] \quad (5)$$

where Qo is the extra-terrestrial radiation, expressed in Joule m^{-2} day^{-1}, having been determined by the expression below:

$$Qo = 38.32 * 10^{6} [h * sin\,\delta * sin\,\varphi + \cos\delta * \cos\varphi * sinH] \quad (6)$$

where 38.32 * 10^6 is the mean value of corrected solar constant converted into Joule m^{-2} day^{-1}, given by CROMMELYNK and FICHOT (1997), H is the semi-arc from the meridian crossing of the sun to the sunset time in degrees, h is the diurnal semi-arc in radians, δ is the solar declination in degrees, and is the local latitude in degrees.

The equations that defined ä, H, and N (PEREIRA et al., 2003) were:

$$\delta = 23.45 * \sin\left[\frac{360}{365} * (DJ - 80)\right] \quad (7)$$

where DJ is the number of days computed since the first day of January up to the considered date.

$$H = \arccos\left[-\tan\delta * \tan\varphi\right] \quad (8)$$

$$N = \frac{2 * H}{15} \quad (9)$$

The number of hours of insolation (n) was measured with a Campbell-Stockes sunshine recorder installed at the four weather stations where the study was carried out.

All the climatic elements used as input variables of the potato potential yield model were obtained from conventional weather stations set up at the experimental research areas of the Agronomic Institute of Campinas, IAC, University of São Paulo, ESALQ/USP, and State University of São Paulo, FCA/UNESP. These governmental Institutions of the State of São Paulo provided the necessary meteorological information for the municipalities of Itararé, Tatuí, Piracicaba, and São Manuel, SP, Brazil.

The climate of Tatuí (23º22'S, 47º52'W Gr., and 600 m), Piracicaba (22º43'S, 47º25'W Gr., and 580 m), and São Manuel (22º44'S, 48º34'W Gr., and 700 m) cities according to the Kõppen System is classified as Cwa or sub-tropical with rains in the summer and dry winter. The climate of Itararé city (24º06'S, 49º20'W Gr., and 1150 m) in the State of São Paulo, Brazil, is classified as Cfb or rainy temperate of altitude, constantly wet throughout the year.

The values of C(T) equal to 0.6 and 0.5 were adopted, respectively, whenever the mean air temperatures throughout the crop-growing season were below or above 20ºC, as recommended by DOORENBOS and KASSAM (1979). The value of C(LAI) was calculated by the equation described by VILLA NOVA et al. (2001) as follows:

$$C(LAI) = \frac{1 - e^{-0.8*LAI}}{2} \quad (10)$$

The ratio between harvested yield and net total dry matter is given by the harvest index (HI) for high-producing cultivars under irrigation. For potato crop, whose commercial product is the tuber, HI varies from 0.55 to 0.65 (DOORENBOS and KASSAM, 1979). For practical purposes, we adopted the mean value corresponding to 0.6 to calculate the final crop production.

Leaf area index (LAI) for the cultivar Itararé (IAC-5986) of potato (*Solanum tuberosum* L.) was determined experimentally in the field by VARILLAS (1991) and ROBLES (2003) under the climatic conditions of Itararé and Piracicaba, SP, Brazil.

The dry matter content of the tubers is intimately related to the tuber specific gravity. To measure tuber specific gravity the weight-in-air/weight-in-water method was used. For that, a random sample of tubers was first weighed in air (Wair) and, after submerging the tubers in water, weighed again (Wwater). Thus, specific gravity (SG) was calculated using the following formula (STARK and LOVE, 2003):

$$SG = \frac{Wair}{Wair - Wwater} \quad (11)$$

Dry matter content of the tubers in percentage, was determined by the expression described by RAMOS (1999) as a function of the specific gravity as follows:

$$DM = 24.182 + 211.04 * [SG - 1.0988] \quad (12)$$

The calculated values of the potential yield obtained by the proposed method were correlated with the observed data from the production fields. As the values of correlation and determination coefficients analyzed separately can lead to interpretations not always suitable for the performance of the studied model, the agreement index *d* was also used (WILLMOTT et al., 1985). A new index *c* proposed by CAMARGO and SENTELHAS (1995) was also adopted in this paper to indicate the performance of the model, putting together the accuracy *R* and the exactness *d* indices, being defined by the multiplication between both indices.

3. RESULTS AND DISCUSSION

Making use of the mean values of global solar radiation flux density, photoperiod duration, photosynthetically active radiation and air temperature along with the maximum rates of carbon dioxide assimilation obtained by the equation 3, required as the input variables of the proposed model in the current study, potato potential yield for the cultivar Itararé (IAC 5986) was calculated throughout fifteen crop growing seasons at four different regions of the State of São Paulo, Brazil (Tables 1 and 2).

Tuber potential yields calculated by the agrometeorological model in study and potential yields harvested from the production fields were highly correlated, since the statistical analysis shows that over 92% of the potential yield variations can be explained by the calculated values. The corresponding values of tuber dry matter estimated by the model varied from 16.8 to 35.7 t ha^{-1}, whereas those of tuber dry matter obtained from the production areas with an adequate soil water supply were within the range varying from 17.5 to 39.0 t ha^{-1} (Table 2). The larger difference between measured and estimated tuber yield was observed for the growing period September through January of the years 1998 and 2003, when the model slightly underestimated and overestimated potential yield at 3.3 and 3.5 t ha^{-1}, respectively.

In the most important potato production areas of Argentina, Caldiz and Struit (1999) reported that actual yields vary from 13 to 30 t ha^{-1}, whereas potential yields of ware potato estimated by the LINTUL-POTATO simulation model were to be within the range of 47 to 126 t ha^{-1}. Differences between actual and potential yield might be attributed to suboptimal solar radiation interception by the foliage, cultivar, seed management, physiological age of the seed, suboptimal management of water and fertilizer, and control measures of early blight and late blight.

The potential yield of agronomic crops is dramatically affected by the amount of water applied during the crop-growing season at a given region. Water and temperature are important climatic elements to be taken into account in crop weather modelling studies. Cooler temperatures result in delayed maturity, which provides more time for the interception of global solar radiation flux density and conversion of intercepted radiation into dry matter. Stark and Love (2003) point out that two major factors influence tuber yield: a) photosynthetic activity and duration of the leaf canopy, and b) the length of the linear tuber growth phase. The longer a canopy is able to produce photosynthate at a relatively high rate, and the longer tubers are bulking at their maximum rate, the higher the yield will be in such a way as to express the productive potentiality of potato crop at a given site.

Table 1. Climatic elements throughout different years and growth periods of the potato crop, cultivar Itararé (IAC 5986), grown at Itararé, Tatuí, Piracicaba, and São Manuel, State of São Paulo, Brazil

Region	Year	Growth period	Cycle days	T °C	n/N	Qg	PAR
						J m^{-2} s^{-1}	
Itararé	1985	Mar./Jun.	100	16.5	0.57	395.0	176.3
	1993	Sept./Jan.	137	18.0	0.45	429.8	194.4
	1994	Mar./Jul.	114	16.0	0.54	382.5	170.0
	1997	Feb./Jul.	140	16.5	0.57	411.0	181.1
	1998	Apr./Aug.	112	15.0	0.57	378.3	167.9
	1998	Sep./Jan.	117	18.0	0.33	372.0	173.5
	1999	Mar./Jul.	126	15.6	0.55	388.0	172.8
	2000	Nov./Mar.	133	20.2	0.49	452.1	204.1
	2001	Mar./Jul.	102	16.9	0.55	392.2	173.5
	2003	Sep./Jan.	98	17.5	0.43	415.9	188.8
	2005	Mar./Jul.	133	16.7	0.58	400.6	177.0
	2005	Oct./Mar.	122	18.7	0.41	413.8	190.2
Tatuí	2001	Sep./Jan.	115	22.8	0.55	480.0	212.5
Piracicaba	1989	Oct./Feb.	105	23.6	0.58	503.0	222.2
S. Manuel	2000	Aug./Jan.	131	14.8	0.56	380.4	168.6

T = daily air temperature; n/N = insolation ratio; Qg = global solar radiation flux density; and PAR = photosynthetically active radiation. Monthly average values.

Table 2. Cultivar characteristics throughout different years and growth periods of the potato crop, cultivar Itararé (IAC-5986), grown at Itararé, Tatuí, Piracicaba, and São Manuel, State of São Paulo, Brazil, and the respective potential yield data

Region	Year	Growth period	CDA	LAI	C(LAI)	C(T)	HI	DM	EPY	MPY
Itararé	1985	Mar./Jun.	41.0	4.34	0.480	0.6	0.6	25.0	17.5	17.5
	1993	Sep./Jan.	41.5	4.34	0.480	0.6	0.6	25.0	27.9	26.4
	1994	Mar./Jul.	41.0	4.34	0.480	0.6	0.6	17.8	27.8	28.2
	1997	Feb./Jul.	41.0	4.34	0.480	0.6	0.6	18.9	32.9	30.8
	1998	Apr./Aug.	41.0	4.34	0.480	0.6	0.6	22.3	21.4	20.3
	1998	Sep./Jan.	41.0	4.34	0.480	0.6	0.6	16.5	35.7	39.0
	1999	Mar./Jul.	41.0	4.34	0.480	0.6	0.6	17.8	30.7	31.6
	2000	Nov./Mar.	42.0	4.34	0.480	0.5	0.6	18.0	32.0	31.5
	2001	Mar./Jul.	41.0	4.34	0.480	0.6	0.6	22.3	19.8	19.5
	2003	Sep./Jan.	41.5	4.34	0.480	0.6	0.6	16.8	29.7	26.2
	2005	Mar./Jul.	41.0	4.34	0.480	0.6	0.6	22.3	25.9	25.2
	2005	Oct./Mar.	41.5	4.34	0.480	0.6	0.6	19.7	32.0	32.7
Tatuí	2001	Sep./Jan.	46.7	4.34	0.480	0.5	0.6	17.8	30.9	29.2
Piracicaba	1989	Oct./Feb.	47.7	2.50	0.423	0.5	0.6	16.0	16.8	18.0
S. Manuel	2000	Aug./Jan.	40.7	4.34	0.480	0.6	0.6	16.0	32.0	33.1

CDA = Carbon dioxide assimilation maximum rates (μL cm^{-2} h^{-1}); LAI = leaf area index; C(LAI) = correction factor for leaf area index variation; C(T) = correction factor for maintenance respiration; HI = harvest index; DM = dry matter content (%); EPY = estimated crop potential yield (t ha^{-1}); MPY = measured crop potential yield (t ha^{-1}).

As to the effect of water application on the productive potentiality expression of potato in a determined climatic locality, Bowen (2003) reported that a reduction of only 62 mm in water applied resulted in a decrease in fresh tuber yield from 38.2 to 30.3 t ha^{-1}. For the summer potato crop, applied water ranged from 380 to 584 mm and the associated yields ranged from 12.1 to 25.4 t ha^{-1}. Therefore, about half as much water was used during the winter to produce 150% more yield than was obtained throughout the summer crop-growing season.

The differences observed on the dry matter content throughout different years and growth periods of the potato crop (Table 2) might be ascribed to climatic variations on tuber specific gravity. Apart from the primary environmental factors affecting specific gravity of irrigated potatoes (air and soil temperatures), other weather conditions can also affect tuber specific gravity. Stark and Love (2003) allege that high evaporative demand caused by low relative humidity, high global solar radiation flux density, and/or high wind speed can reduce photosynthesis by causing stomata to close with an accompanying restriction of CO_2 uptake. Prolonged periods with overcast skies can also reduce light intensity to levels below that required for maximum dry matter production.

The coefficient of determination R^2 and correlation R bring information about the degree of accuracy, but do not reveal the exactness of the model. The index of agreement d proposed by Willmott (1985) reveals a high level of exactness with a value of d equal to 0.981. The index c has assumed a value of 0.945 for the studied sites, showing an excellent performance, according to the interpretation criterion of the performance of mathematical models presented by Camargo and Sentelhas (1995). Figure 1 indicates that both accuracy, given by the trend line, and the exactness of the model, demonstrated by the dispersion of the data around the fitted 1:1 line of the estimates, were rather satisfactory. The value of c was higher than 0.93, exceeding, however, values of d considered as satisfactory, whose lower limit recommended by Robinson and Hubbard (1990) is of 0.75.

The results showed that the agrometeorological model tested under the climatic conditions of the State of São Paulo, Brazil, in general underestimated irrigated potato yield by less than 10%. This justifies the recommendation of performance test evaluation of the proposed model at other climatic regions, for different crops and genotypes under optimal irrigation conditions in further scientific investigations.

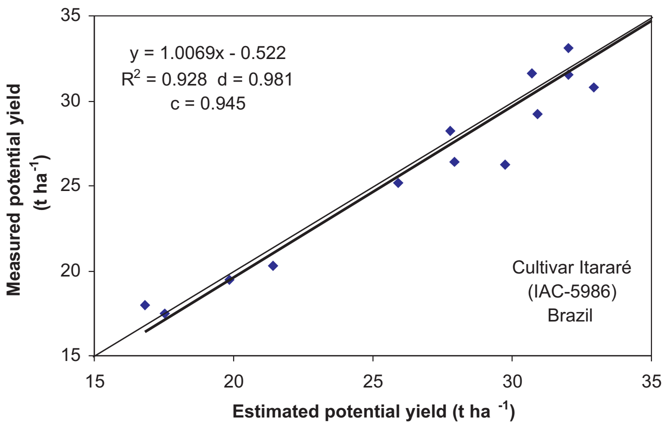

Figure 1. Relation between observed and estimated values of potato crop potential yield, cultivar Itararé (IAC-5986), at the State of São Paulo, Brazil.

4. CONCLUSION

The agrometeorological model taking into account information on leaf area index, photoperiod duration, photosynthetically active radiation and air temperature is feasible to estimate potential tuber yield at a commercial scale. The performance test shows that it can be used to forecast harvest time, and also as an effective tool to predict the suitability of potential regions to the cultivation of potato crops, cultivar Itararé (IAC-5986), at the State of São Paulo, Brazil.

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