Coffee Genetic Breeding at IAPAR

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ABSTRACT

This paper introduces the coffee genetic breeding research program developed by IAPAR (Agronomic Institute of Paraná, Brazil) which started in 1973. The characteristics of a breeding program for a seed-propagated perennial plant with a biennial production and the difficulties in assessing yield and longevity due to the time limitations they impose on the development and release of commercial cultivars are presented. A concise diagnosis of the arabica coffee crop in the region and the cultivar management and developmental strategies and priorities within the "IAPAR Model for dense population coffee crop" are detailed. The advances in cultivar development and management, integrated with other technologies for the solution of main problems are discussed and, an array of alternative procedures, techniques, methods and strategies to reduce the coffee cultivar development time from 24 to 12 years are proposed.

KEY WORDS: Coffee breeding, Coffee quality, Coffee nematodes, Coffee rust, Perennial-crop breeding.

INTRODUCTION

Quantitative characteristics such as yield are more difficult to work in coffee than in any other annual plant breeding since the coffee tree has a juvenile period. Also, yield needs to be assessed for several consecutive years in order to have an accurate prediction of the tree long-term production capacity, because of a sharp annual oscillation of production where the plantation is exposed to full sunlight without shading (Stevens, 1949).

Despite these limiting factors, breeding programs carried out at several research centers have obtained highly satisfactory genetic progress. For example, the breeding program started at the Agronomic Institute of Campinas in 1933 achieved progresses of up to 240% when the Mundo Novo cultivar was compared to the Arabica, the first cultivar planted in Brazil (Fonseca et al., 1978).

The most common breeding methods used in Brazil consist of selecting individual plants followed by progeny assessment or an intra- and inter-specific hybridization and genealogical selection. The backcross method has also been applied to transfer specific traits to *Coffea arabica* (L.), such as short internodes and pest and disease resistance, which are present in other cultivars or related species. Individual plant selection can be carried out either in commercial crops or in experimental plots especially planted for breeding purposes. In the later case, yield is recorded for several successive years to identify superior genotypes (Medina et al., 1984; Carvalho, 1988).

An in-depth knowledge of the cultivation environment and technology, processing, commercialization and consumer demands is fundamental to the development of successful coffee cultivars. Coffee breeding programs aim at increasing profits and providing economic stability to coffee farmers through efficient production at the farm level (figure 1, 2 and 3). The coffee genetic breeding program at IAPAR is based on the "IAPAR Model for dense population coffee crop" (more than 8,000 plants/ha), which involves more than 80 technologies (Sera et al., 1994). The increase in production efficiency is attained through:

1) Yield increase;
2) Reduction of production cost per bag;
3) Improvement in product quality; and,
4) Greater production stability.

Figure 1 - The genetic potential for yield / plant of coffea cultivars is very high.

Figure 2 - Wide space conventional cultivation

Figure 3 - High density cultivation system

ANNUAL GENETIC GAIN OBTAINED BY SELECTION

Coffee improvement has some important characteristics that require the adoption of special procedures to avoid low efficiency in breeding programs (Sera and Alves, 1999). These special characteristics include:
– longer periods are needed to obtain flowers for crossing and seed production;
– greater importance of an accurate assessment of all the agronomic characteristics due to the relatively high cost of cultivar substitution;
– high cost of field trials due the larger area and longer time required for evaluation;
– production earliness and longevity assessments;
– an evaluation of the annual yield oscillation; and,
– annual flowering and yield on the same plant.
These characteristics limit the adoption of some traditional breeding methods normally used in annual crops and, therefore, lower the efficiency measured by the low genetic gain from selection in each year (G.S.a).

Seed derived cultivar

Only the s^2_a can be used in the selection (where: $\sigma^2_G = \sigma^2_a + \sigma^2_d + \sigma^2_i$) and, consequently, populations have to be conducted for some generations until greater levels of homozygosis are obtained to allow fixation of favorable traits. Thus, this procedure results in a much lower G.S.a than those propagated vegetatively or that obtained for annual plant breeding (F_n = 1 year). In the estimation of genotipic determination coefficient for the biennial yield mean (b_{p2}) of selected lines (Sera, 1980), the σ^2_g (genotypic variance) component includes the σ^2_{ga} interactions (interaction between the genotypic variance x year variance), the σ^2_{gl} (interaction between the genotypic variance x locality variance) and the σ^2_{gla} (interaction among the genotypic variance x year variance x locality variance). The consequence is an overestimation of the genotypic effect of the lines. As in many presently available cultivars, it requires homozygosity in the majority of the loci, thus the G.S.a is very low and demands at least 6 years per cycle and four selection cycles (F_n).

$$\text{Line G.S.a.} = \text{D.S.} \times \frac{\sigma^2_a = \sigma^2_G}{\sigma^2_a + \sigma^2_d + \sigma^2_i + \sigma^2_e = \sigma^2_F} \div (\text{Years per Cycle} \times F_n)$$

G.S.a = genetic gain from selection per year;
D.S. = Selection differential;
s^2_F = Phenotypic variance;
s^2_G = Genetic variance;
s^2_a = Additive genetic variance;
s^2_d = Dominant genetic variance;
s^2_i = Epistatic genetic variance;
s^2_e = Environmental variance.

F_n = number of selection generations needed to obtain cultivars.

Clone-type cultivar

If coffee is vegetatively propagated, then $\sigma^2_G = \sigma^2_a + \sigma^2_d + \sigma^2_i$ and the expected genetic gain per year is:

$$\text{Clone G.S.a.} = \text{D.S.} \times \frac{\sigma^2_a + \sigma^2_d + \sigma^2_i = \sigma^2_G}{\sigma^2_a + \sigma^2_d + \sigma^2_i + \sigma^2_e} \div \text{Years / Cycle}$$

That is, all the σ^2_G could be exploited, which in a superior genotype would generally include heterozygozity and heterosis. These favorable characteristics would be vegetatively transmitted to the later generations, resulting in a greater G.S.a than that obtained for seed propagated cultivars, since the respective genotipic determination coefficients ($b_{p2} = s^2_G / s^2_F$) have $\sigma^2_G = \sigma^2_a + \sigma^2_d + \sigma^2_i$ and $\sigma^2_G = \sigma^2_a$ in the numerator, respectively. Clone G.S.a is also greater because the $F_n = 1$ instead of 3 or 4.

Depending on the type of coffee tree propagation and the type of cultivar required **(Table 1),** the length of time needed may vary. For instance, selections conducted from early generations and a reduction in the number of cycles from four to three would result in a six to eight years gain. The number of years per cycle can also be reduced from eight to four or three years when an anticipated selection for yield is used. However, if methods that do not assess yield are used, the number of years per cycle can be reduced to two only. The time saved in three breeding cycles would amount to eight, 11 or even 14 years considering that at least six years of regional competition trials are required to obtain accurate results. The reduction in the number of years and in the number of cycles is the key to increased efficiency and to the annual genetic progress in coffee breeding.

Table 1 - Time spent obtaining coffee cultivars using different alternatives.

ALTERNATIVES	(1) Experimental Cultivars	(2) Regional assessment	(3) Multiplication	(4) Commercial production
(A) Line	14	22	26	30
(B) Line + early generation	8	16	20	24
(C) Line + early generation + early selection	8	12	16	20
(D) Line + Early Generation + SSD	7	10	14	18
(E) Line + Early Selection + Backcross	7	10	14	18
(F) F_2 Hybrid	6	10	14	18
(G) F_1 Hybrid	2	8	8	12
(H) Clone	2	8	8	10
(I) C + Early release (2, 3 and 4 simultaneously)	8	12	12	12
(J) D + Early release (2, 3 and 4 simultaneously)	7	10	10	10

Figure 4 - Juvenile selection in the field

Figura 5 - Selection by index in the 1st *harvest*

Figure 6 - Selection by index at first flowering

CULTIVAR DEVELOPMENT IN REDUCED TIME

The possibility of developing a coffee breeding program involving the multiple objectives mentioned in this paper, such as backcrossing and recurrent or genealogical selection, will depend greatly on the reduction in the number of selection cycles and on the early selection for yield, using fewer assessment years per generation. Other less complex traits such as pest and disease resistance and environmental stress tolerance can be assessed and submitted to selection during the juvenile period (Sera, 1984; 1987).

Development of line-type cultivars includes the establishment of a segregant population, a genotype selection, yield trials and superior genotype release for seed production. The time taken for each selection generation may vary considerably (Table 2 and 3). The breeder needs to develop strategies which use human resources, materials and available time rationally to obtain the greatest possible gain per year with the least cost.

There are alternative procedures, methods and techniques that reduce significantly the time spent and the number of plants to be assessed in the field during the process of cultivar development:

1. Reduction of the juvenile period (Figure 7);
2. Selection during the juvenile period (Figure 4);
3. Selection in early generations;
4. Anticipated selection for yield in the first years;
5. Methods that do not assess yield (bulk, SSD and backcross);
6. Biotechnological techniques/genetic engineering;
7. Di-haploid cultivars;
8. Heterosis expressed in the F_1, F_2 generations and in synthetic hybrid cultivars (Figure 8);
9. Vegetative propagation for the use of clone-type cultivars; and (Figure 9),
10. Anticipated release of cultivars.

Figure 7 - Reduction of juvenile period in a greenhouse nursery.

Figure 8 - Manually produced hybrid seeds for small farms.

Figure 9 - conventional cloning.

Table 2 - Example of early generation selection with juvenile period reduction and line-type cultivars early release.

Month/Year	Description of Line Development Events and Stages
Sept/Y0	20 Crosses, 1000 plants/Cross, Complementary Parents
Dec/Y1	Planting, 100 plants/$F_{1,}$ 20 Hybrids
Dec/Y3	Planting, 2000 plants/$F_{2,}$ 05 Families
Dec/Y5	Planting, 30 plants/$F_{3,}$ 45 Progenies
Dec/Y6	Planting, 30 plants/F_4, Generation advance, 45 progenies
Dec/Y7	Planting, 30 plants/F_4, Regional trial, 45 progenies
Dec/Y7	Planting, 500 plants/F_4, Seed multiplication field, 45 progenies
Sept/Y12	Release of 3 cultivars, 500kg of F_5 seeds/cultivar

DEVELOPMENT OF COFFEE CULTIVARS TO SOLVE DIFFERENT PROBLEMS

More breeding research projects should be developed to achieve greater efficiency in coffee production quality at a lower cost and greater yield to solve or reduce limiting factors. The main breeding activities and research projects developed by IAPAR and the advances achieved through breeding to solve the main problems of the Paraná coffee plantations are presented next.

Diagnosis and research priorities in coffee breeding

Breeding a seed propagated perennial crop such as coffee requires a detailed diagnosis of yield potential, quality and production cost per bag as well as of the viability of the solutions proposed to maximize these potentials. As coffee is a perennial plant with a productive life ranging from 10 to 20 years, the successful cultivar characteristics must be projected 20 years in advance. A simple diagnosis of the research needs in coffee breeding can be summarized as follows:

1) To improve and make available the coffee genetic potential for quality and yield (6,000kg coffee grains/ha) at lower production costs/bag;
2) To adapt cultivars to mechanized cultivation and harvesting whenever human labor is short;
3) To adapt cultivars in order to reduce climatic risks such as frost, heat, drought as well as edaphic risks such as nutritional and physical factors;
4) To continue improving cultivars for new rust pathotypes resistance;
5) To continue developing cultivars resistant to the *Meloidogyne paranaensis*, *M. incognita* and other nematodes;
6) To develop insect resistant cultivars such as the leaf miner (*Perileucoptera coffeella*) and the fruit borer (*Hypotenemus hampei*);
7) To develop cultivars resistant to potential bacterial (*Pseudomonas*) and fungal diseases such the fruit anthracnose (*Colletotrichum kahawae*) and fusarium (*Fusarium spp*);
8) To develop cultivars through genetic transformation for traits not present in the *Coffea* genus, such as uniform ripening, borer resistance, full spectrum herbicide resistance and nutritional components such as any vitamin in the beans;
9) To reduce the time spent to develop a cultivar from 24 to 12 years;
10) To incorporate new breeding techniques such as cloning, haploidy, genetic transformation and DNA marker assisted selection.

Criteria for agronomic assessment

Feasible assessment criteria are fundamental for easy, fast and fairly precise genetic material trait evaluations in thousands of coffee trees. The main agronomic traits assessed and evaluation criteria are:

1) Visual plant assessment. A subjective visual scoring of the tree general merit, from 1 to 5 (1 = bad; 2 = regular; 3 = good; 4 = very good and 5

= excellent). Assessed in January, February and March.
2) Yield. In liters of cherry fruits/tree assessed visually for the best progeny in initial generations. In kg of coffee grains/tree with 12% humidity for the best progeny in regional trials.
3) Tree vigor. Subjective scoring from 1 to 5 (1 = bad; 2 = regular; 3 = good; 4 = very good and 5 = excellent) for the best progenies, carried out at harvest.
4) Early fruit maturity. Subjective scoring from 1 to 5 (1 = early; 2 = semi-early; 3 = semi-late; 4 = late; 5 = very late) assessed for the best progeny at harvesting.
5) Biennial production oscillation. Assessed as the percentage difference between the lowest yield and the mean biennial yield.

Table 3 - Compared time to develop line-type cultivars using the genealogical, early generation selection, abbreviated early generation selection, abbreviated single seed descent (SSD) and backcross (BC) methods of selection in *C. arabica* L. breeding.

	BREEDING METHODS				
Year	**Genealogical**	**Early Generation Selection**	**Abbreviated Early Generation Selection**	**S.S.D. + Abbreviated Selection**	**Dominant BC gene + Abbreviated Selection**
1	F_1 Plant	F_1 Plant	F_1 Plant	F_1 Plant	F_1RC_1 Plant
2	Harvest & planting	Harvest & planting	Harvest & planting	Harvest & planting	Flowering & BC_2
3	Flowering	F_2 & flowering	F_2 & flowering	F_2 & flowering	Plant F_1RC_2
4	1^{st} Harvest	1^{st} Harvest	1^{st} Harvest	Harvest & planting	Flowering & BC_3
5	2^{nd} Harvest & planting	2^{nd} Harvest & planting	2^{nd} Harvest & planting	F_3 & flowering	Plant & F_1RC_3
6	F_2 & flowering	F_3 and flowering	F_3 & flowering	Harvest & planting	Flowering & ⊗
7	1^{st} Harvest	1^{st}. Harvest	1^{st} Harvest	F_4 and flowering	F_2 & homozigous
8	2^{nd} Harvest & planting	2^{nd} Harvest & planting	2^{nd} Harvest & planting	1^{st} Regional Test	1^{st} Regional Test
9	F_4 & flowering	F_4 & flowering	F_4 & flowering	2^{nd} Regional Test	2^{nd} Regional Test
10	1^{st} Harvest	1^{st} Regional Test	1^{st} Regional Test	CULTIVAR	CULTIVAR
11	2^{nd} Harvest & planting	2^{nd} Regional test	2^{nd} Regional Test	Basic seed	Basic seed
12	F_5 Flowering	3^{rd} Regional test	CULTIVAR	Flowering	Flowering
13	1^{st} Harvest	4^{th} Regional Test	Basic seed	1^{st} Yield	1st Yield
14	2^{nd} Harvest & planting	5^{th} Regional Test	Flowering	RELEASE	RELEASE
15	F_6 & flowering	6^{th} Regional test	1^{st} Yield	Commercial seed	Commercial seed
16	1^{st} Regional Test	CULTIVAR	RELEASE	Flowering	Flowering
17	2^{nd} Regional test	Basic seed	Commercial seed	*COFFEE CROP*	*COFFEE CROP*
18	3^{rd} Regional Test	Flowering	Flowering		
19	4^{th} Regional Test	1^{st} Yield	*COFFEE CROP*		
20	5^{th} Regional Test	RELEASE			
21	6^{th} Regional Test	Commercial seed			
22	CULTIVAR	Flowering			
23	Basic Seed	*COFFEE CROP*			
24	Flowering				
25	1^{st} Yield				
26	RELEASE				
27	Commercial Seed				
28	Flowering				
29	1^{St} Harvest				
30	*COFFEE CROP*				

6) Productive longevity. Assessed as the percentage difference between the annual yield of the first biennial and the annual yield of the last biennial.
7) Percentage of empty fruits. Assessed by counting samples of 10, 20 or 50 fruits of the best progenies at harvesting.
8) Bean size. Subjective scoring (1 = tiny; 2 = small; 3 = medium; 4 = big; 5 = gigantic) for the best progeny.
9) Plant size. Visual and subjective assessment from 1 to 5 (1 = very small (Ct-Sb-); 2 = small ('Iapar 59'); 3 = medium ('Catuaí'); 4 = big ('Acaiá'); 5 = very big ('Icatu IAC2944'). Height and diameter evaluation (in centimeters) in the best progenies after 8 years of production.
10. Organoleptic quality of de-hulled coffee for the best materials.
Sweetness. Taste and determination of total sugars.
Body. Taste and determination of oil content, total proteins and soluble solids.
Aroma. Sensorial test.
Acidity. Taste and titer acidity determination.
Bitterness. Taste and caffeine content determination.

Germplasms bank

The IAPAR coffee germplasm bank contains the following materials:
1. *C. arabica* cultivar lineages: Catuaí Amarelo, Catuaí Vermelho, Mundo Novo, Acaiá, Icatu Vermelho e Icatu Amarelo, Iapar-59, Tupi, Obatã, Rubi, Topázio, Acaiá Cerrado, Colômbia, Colômbia Amarelo, Costa Rica 95, Catsic, Tecsic and Pacamara.
2. *C. arabica* assessions from Ethiopia: 144
3. *C. canephora* var. *kouillou* populations: 15.
4. *C. canephora* var. robusta populations: 10.
5. Botanical varieties and *C. arabica* mutants: Arabica, Laurina, Semperflorens, Maragogipe, Cera, Caturra, Caturra Amarelo, Bourbon, Bourbon Amarelo, Semi-erecta, Erecta, Ennarea, Cioicie, Geisha, Goiaba, Polisperma and Bullata.
6. Other *Coffea* species: *C. liberica* var. *dewevrei; C. eugenioides*; *C. racemosa*; C. *kapakata* and *C. stenophylla.*
7. Interspecific populations: "Arabusta" = (C. arabica x *C. canephora*) 4n, "Piatã" = (C. *arabica* x *C. liberica* var. *dewevrei*) 4n, (*C. arabica* x *C. racemosa*) 4n, "Timor Hybrid" = [(*C. arabica* x *C. canephora*) 4n x *C. arabica*] and "Icatu" = {[(*C. canephora* 4n x *C. arabica*) x *C. arabica*] x *C. arabica*}.
8. *C. arabica* progenies carrying genes from *C. canephora* and *C. liberica* var. *liberica* e var. *dewevrei:* 50 from "Icatu x Catuaí", 10 from "Mundo Novo Sh_3" = {[(*C. arabica* x *C.liberica*) 4n x *C. arabica*] x *C. arabica*} x "Mundo Novo"}, 20 from "Catuaí Sh_3" = {[(*C. arabica* x *C.liberica*) 4n x *C. arabica*] x *C. arabica*} x 'Catuaí'}, 20 from "Catuaí Sh_3" x "*C. arabica* Sh_2", 5 from "Catuaí Sh_1" x "*C. arabica* Sh_4", 20 from "Catimor" = 'Caturra' x "Timor Hybrid 832-1", 50 from "Sarchimor" = 'Villa Sarchi' x "Timor Hybrid 832-2", 80 from "Icatu x Catuaí", 10 from 'Iapar-59' x "(Icatu x Catuaí)", 10 from 'Iapar-59' x 'Mundo Novo', 'Iapar-59' x "Catuaí Erecta", 'Iapar-59' x "Super-Precoce", 15 from "Piatã" x 'Catuaí' and {[(*C. arabica* x *C. racemosa*) 4n x *C. arabica*] x 'Tupi'}.

Cultivars adapted for cultivation systems

Alternative cultivation systems and their respective preferential cultivars are:
1) Conventional (>3.0 x 0.6m spacing). Large-size trees such as 'Mundo Novo' and 'Icatu' and medium-size trees such as 'Catuaí'.
2) Semi-dense (2.5 x 0.6m). Medium-size and small-size trees such as 'Catuaí' / 'Obatã' and 'Iapar-59' / 'Tupi', respectively.
3) Dense (2.0 x 0.5m). Compact architecture, small and medium- size trees such as 'Iapar–59' / 'Tupi' and 'Catuaí', respectively.
4) Super dense (<1.5m x 0.5m). Small and medium- size trees such as 'Iapar 59' / 'Tupi' and 'Obatã'.

Several genotypes such as the germplasm Sarchimor, Catimor, Icatu, Catuaí x Icatu, Sarchimor x Catuaí and Sarchimor x Mundo Novo are being developed. They were selected for dense planting and are under regional testing at different spacings to assess yield per area, quality and crop management and harvest costs.

Cylindrical-cone, cone or erect canopy architecture can increase yield per area in dense and super-dense plantings due to better light penetration on the productive nodes. The early production trait of small cultivars derived from the Caturra, Catimor and Sarchimor germplasms may be important to intensive cropping systems whether or not they have been irrigated, mechanized and systematically pruned.

Cultivars with special qualities

The development of a coffee production potential with the quality demanded by consumers has undergone several difficulties. Uniform maturity, scheduled harvesting and larger beans are required along with the normal attributes such as body, aroma, acidity and sweetness. As for other special crop characteristics such as less toxic residue, the use of cultivars resistant to most of the limiting parasites helps in their production.

All recommended coffee cultivars have the potential for fine and extra-fine quality coffee, which can be obtained through correct management in different environments and cultivation systems. Special emphasis must be placed on technologies that guarantee quality at pre-planting, pre-harvesting and harvesting, followed by suitable post-harvesting processing, packing and roasting techniques.

a) Pre-harvest quality

The correct use and management of cultivars during the pre-harvesting period is very important to ensure quality. Each cultivar has unique characteristics regarding the many factors that influence quality. These factors include bean chemical composition, planting spacing, pruning, nutrition and phytosanitary management, product preparation and roasting technology.

a1) Quality vs. Nutrition

Since they are smaller than the 'Catuaí', produce larger beans and allow greater number of trees/ha, the new coffee cultivars are frequently 20% more productive per area. Under a 20% deficiency rate in nutrients, nutritional "die-back" will occur together with less vigorous plants and badly nourished and unhealthy fruits, and, consequently, poor quality.

a2) Quality vs. Cercospora coffeicola disease

Badly nourished coffee trees may have greater incidence of nutritional diseases such as that caused by *Cercospora coffeicola*. These badly nourished beans, besides having no chemical quality even in cultivars such as 'Catuaí', they also produce beans which are deficient in sugar, an important quality component, and may acquire a strange chemical flavor or fungus taste.

b) Pre-planting quality

The selection of cultivars with high bean quality and other special qualities is fundamentally important during the pre-planting period since after they've been planted, changes can occur only through cultivar substitution. Planting inadequate cultivars in a state, region or property will result in inferior quality or a lower proportion of quality coffee.

b1) Cultivar choice for quality

The use of a combination of four cultivars belonging to different maturity groups, from early to late, as already explained in a previous item, is fundamental to increase the production of a greater proportion of quality coffee at a lower cost. Late cultivars should be avoided in cold regions to reduce irregular maturity and, similarly, early cultivars should not be planted in hot areas to reduce incomplete chemical maturity. Earlier or later cultivars should be also used according to the rainfall pattern in the region to avoid excessive moisture at harvest.

Figure 10 - Cultvars: **left =** Tupi, **right =** Icatu Precoce

Figure 11 - Cultivars: ***Left*** = *Catuaí*, ***right*** = *Iapar 59*

Late cultivars should be avoided in areas prone to frosts which affect unripe fruits. Yellow fruit cultivars should not be planted on properties that use the manual harvest system for production of depulped cherry fruit, since immature fruits can be confused with yellow fruit at the ideal maturity stage.

b2) Cultivar unique quality

Advanced high yielding lineage cultivars are analyzed for quality (Sera and Bacetti, 2000) initially by the cup test using the ABIC system. Then quality is detailed by submitting the coffees to OIC and "expresso" coffee panels, where all the quality components such as fragrance, aroma, astringency, sweetness, body, acidity, roast quality and strange flavors are determined. There is the possibility of developing special quality cultivars with different aromas, lower or higher caffeine content, higher soluble solids content, more or less body, bigger fruits, etc., especially those coffees which are healthier due to pest, disease and nematode genetic resistance. Cup quality seems to be a dominant inherited trait in C. arabica x *C. Canephora* and *C. arabica* x C. *liberica* var. *dewevrei* crosses (Carvalho, 1988).

b3) Quality variability among cultivars

Quality variability is detected among hundreds of lineages selected from thousands of genotypes derived from germplasms such as Catuaí, Mundo Novo, Icatu, Catimor, Sarchimor, Catucaí, etc. **(Table 4).** After a quality test, these lineages may be registered as cultivars. There is no germplasm which confers quality to all the derived lineages. Many lineages from the Icatu and Sarchimor germplasms, for example, have problems such as a high proportion of shell beans and poor beverage quality, while others from the same germplasm show quality superior to the lineages selected from the same germplasm.

Example of cultivar development IAPARLF 77028 experimental cultivar

It was obtained from the cross between the *Coffea arabica* "Villa Sarchi CIFC 971/10" and "Timor Hybrid CIFC 832/2" carried out in 1960 at CIFC – Coffee Rust Investigation Center, in Portugal. The C1816 – EP141 c.1567 progeny was selected at the Agronomic Institute of Campinas. In 1997, IAPAR introduced this material as IAPAR 77028. The IAPARLF 77028 progeny in the F_5 generation was selected through the genealogical method. To this date it has shown semi-late maturity, similar to that of the Mundo Novo cultivar, and moderate resistance to the types of rust currently identified in the state of Paraná. It is a small plant recommended preferably for dense and super dense cropping at high altitudes with less than 21ºC average annual temperature (Tma). IAPAR 77028 has large fruits, which are yellow when ripe, and its drinking quality is superior to that of the

'Catuaí' or 'Mundo Novo'. Fruit maturity occurs before that of the 'Catuaí' and places the cultivar in the semi-late group, which is suitable for harvest scheduling. It stands out because of its superior drinking quality, which is better than that of the present cultivars.

IAPARLBF77041-62-2 experimental cultivar

It belongs to the Catuaí Sh_2, Sh_3 germplasm and was crossed as IAC H8721 – EP164 c.1420 at the Agronomic Institute of Campinas. The material was received by IAPAR in 1977 and classified as IAPARLF 77041. F_6 generation materials derived from the IAPARLBF77041-62-6 progeny were selected using the genealogical method. They show moderate resistance to the rust types currently identified in the state of Paraná and develop vigorous medium-size plants with late maturity and large red fruits when mature (fruits are larger than those of 'Acaiá'). They are recommended for dense planting and for special markets which prefer large grains and sensorial quality.

Cultivars for reduced harvest and processing costs

Harvesting is one of the most expensive operations in coffee cropping. Quality and, consequently, price depend on proper harvesting, which is the most costly item in the production of one bag of coffee.

a) Echelonned harvest

The adequate use of the available cultivars is essential for a greater proportion of quality coffee at a lower cost (Figures 10 and 11). The recommended cultivars (Sera and Guerreiro, 1999) can be classified as early (e.g. Icatu Precoce), semi-early (e.g. Iapar-59), medium (e.g. Mundo Novo IAC 388-17), semi-late (e.g. Tupi) and late (e.g. Catuaí, Rubi). Early (Emcapa 8111), medium (Emcapa 8121) and late (Emcapa 8131) robusta clonal coffee cultivars are available for echelonned harvest (Bragança et al., 1993). Labor, infrastructure and equipment requirements can be reduced to at least half by blending cultivar cycles. The risk of continuous rainfall during harvesting would also be reduced. Rain can lower bean quality and increase harvest costs by dropping dry beans on the ground.

b) Cultivars in harvest cost reduction

Medium (Catuaí) or small-size (Iapar-59) cultivars with compact canopy architecture increase significantly the productivity of manual and mechanized harvest. Cultivars with more uniform fruit maturity and greater adhesion on the branch after ripening would be of great interest. Genetic transformation using uniform ripening genes (Pereira et al., 2000) would have great impact on the production of a better quality harvest.

Table 4 - Drinking quality of the selected coffee cultivars and germplasms.

Cultivars	Bean sizes P. M. (mesh 14-20=bigger)	Beverage quality: rio, riada, hard and soft		
		Taster 1	Taster 2	Taster 3
IAC 81 from "Catuaí"	16,3	Hard	Hard	Hard
Icatu Precoce (early type) from "Icatu"	16,3	Hard	Hard	Hard
IAC 376-4 from "Mundo Novo"	16,6	$Hard^+$	$Hard^+$	Hard
IAPAR-59 from "Sarchimor"	16,6	$Hard^+$	$Hard^+$	Hard+
(IAPAR-59 x IAC 376-4) F_2	16,7	Hard	Hard	Hard+
(IAPAR-59 x "Icatuaí") F_2	15,9	Hard	Hard	Hard
"Catuaí Sh_2 Sh_3"	17,2	Hard	Hard	Hard
IAPARLF77055 from "Catuaí" x "Icatu"	16,9	Hard	Hard	Hard
C. arabica var. Maragogipe	17,8	$Hard^-$	$Hard^-$	$Hard^-$
IAPARLBF77028 from "Sarchimor"	17,2	$Hard^+$	Hard	$Hard^+$

SOURCE: Sera & Bacetti, 2000.
$Hard^-$ = Hard to worse drinking quality; $Hard^+$ = Hard to better drinking quality

Figure 12 - Echelonned harvest using {early to extra late cultivars] can reduce labor, machine and infrastructure requirements

Example of cultivar development IAPARLBF 77041-55-5 experimental cultivar

Derived from the "Catuaí" x (H7314 – 4 (Sh_2Sh_3) cross made in 1971 by the Agronomic Institute of Campinas and identified as IAC H8721 – EP164 c.1420. The material was received by IAPAR in 1977 and classified as IAPAR 77041. F_5 generation progeny IAPARLBF77041-55-5 were selected using the genealogical method. It presents vigorous medium-size plants, with very late maturity and moderate rust resistance. The red when ripe fruits are larger than those of 'Catuaí'. For better echelonned harvest it is recommended for low altitude sandy soil regions and/or hot regions.

Cultivars adapted to heat, drought and poor soils

Cultivars with less susceptibility to water shortage help improve yield, reduce irrigation costs and optimize the availability of water, which is becoming scarce in regions with occasional or persistent rainfall shortages where irrigation is necessary.

The Robustão Capixaba cultivar (*C. canephora* var *kouillou*) is 30% less susceptible to drought than the clonal cultivars and 75% less susceptible than the seed bred cultivars (Ferrão et al., 1999). Larger cultivars such as those derived from the Icatu and Mundo Novo germplasm seem to tolerate drought better, especially at their initial development stages.

C. arabica genotypes with root systems, canopy architecture and physiological behavior more adapted for drought conditions can be selected. Arabic coffee trees from Ethiopia and *C. arabica* genotypes carrying genes from *C. racemosa*, *C. canephora* and *C. liberica* var. *dewerei* are genetic materials that demands further research. Selections developed in Kenya such as Kenya 1, Kenya 2, SL 28 and

SL30 seem to be less susceptible to drought (Carvalho, 1988). Grafting *C. arabica* cultivars on less drought susceptible *C. canephora* genotypes would be a possible short-term solution.

Brazil has a very large area suitable for coffee cultivation. However, in acid soil areas with low phosphorus availability and low calcium and magnesium levels, genotypes with lower susceptibility to acidity, aluminum and manganese toxicity and high phosphorus absorption efficiency may perform satisfactorily. Coffee tolerance to aluminum is related to phosphorus and calcium use efficiency (Braccini et al., 1998). Passo and Ruiz (1995) reported that the Conilon cultivar (*C. canephora*) was more susceptible to aluminium toxicity than the Catuaí cultivar (C. arabica), but both showed similar susceptibility to manganese. Braccini et al. (1998) classified the coffee genotypes at pH 4.0 and with high aluminum level as tolerant, moderately tolerant, moderately sensitive and sensitive, and indicated the UFV 1359 and UFV 2149 progenies as tolerant.

Coffee trees with greater root volume and absorbent surface are not only less susceptible to soil acidity but are also higher yielding under low nutritional levels. They are recommended for poor soils with most available chemical elements below the acceptable levels. Therefore, vigorous C. liberica var. dewevrei and *C. canephora* genotypes with efficient root systems used as roots-stock or as source of genes to introgress into C. arabica would contribute to the reduction of fertilizer costs and increase yield. Grafted arabic coffee trees on 'Apoatã' (*C. canephora* var. *robusta*) root-stock, which are resistant to nematodes, show higher yield compared to non-grafted trees in soils without nematodes (Fahal et al., 1998).

Examples of developed cultivar

IAPARLF 77055-76-12 Experimental cultivar

Derived from the Catuaí x Icatú (IAC H9878 – EP187 c.684) cross developed at the Agronomic Institute of Campinas in 1972. The material was received by IAPAR in 1977 and named as IAPAR 77055. The IAPAR 77055-76 progeny was submitted to genealogical selection to generate the F_5 IAPARLF 77055-76-12 line with medium-size plants, similar to 'Catuai', and red fruits when ripe. It is a late maturing genotype in lower altitude and sandy soil regions of the state of Paraná, and is recommended for harvest scheduling. It shows moderate susceptibility to the rust types currently identified in the state and can be used in dense cropping systems.

Rust disease *(Hemileia vastatrix)*

Rust control is difficult due to fungicide cost, operational difficulties and unpredictable weather. This disease increases cost, depreciates coffee quality and increases crop susceptibility to frost in the case of inadequate control. New varieties carrying more resistance and tolerance genes need to be developed to prevent the new rust types which can break the current varieties resistance.

Long term breeding programs carried out at many institutions such as the Genetic Section of the Agronomic Institute of Campinas (IAC) and the Federal University of Viçosa (UFV) in collaboration with the Investigation Center of Coffee Rusts (CIFC) have offered new high yielding quality cultivars with either vertical or horizontal resistance to Hemileia vastrix (Bettencourt and Rodrigues, 1988). Cultivars developed by several research centers were released, such as Icatu Vermelho, Icatu Amarelo, IAPAR–59, Icatu Precoce, Tupi, Obatã and Catucaí. These cultivars and other genotypes that are being prepared to be released in the market have shown the high profitability level of the investments being made by genetic breeding research. Table 5 shows an example of a breeding scheme developed to obtain resistant coffee cultivars.

Thousands of plants are field assessed by visual subjective scores for other agronomic characteristics and rust resistance (1 = resistant; 2 = moderately resistant; 3 = moderately susceptible; 4 = susceptible; and, 5 = highly susceptible). The best materials are carefully assessed by phytopathologists from the Coffee Rust Investigation Center (CIFC) for spectrum and degree of resistance to all known world rust physiological races.

Other pests and diseases

a) Fruits anthracnosis *(Colletotrichum kahawae)*

Preventive measures to avoid the introduction of anthracnosis must be taken and studies to develop resistant cultivars should be conducted. The Icatu and other germplasm with C. canephora genes and some C. arabica accessions from Ethiopia have shown resistance. The DNA marker assisted selection will be used in Brazil whenever the virulent strain is unavailable.

b) Bacterial disease *(Pseudomonas syringae pv. garcae*)

Bacterial disease caused by *P. syringae* pv. *garcae* is becoming a limiting factor in certain high altitude regions and also on the slopes of cropping areas facing South and East; therefore, resistant cultivars must be developed. The Sh_1 rust resistance gene also gives complete resistance to this pathogen (Moraes et al., 1974; Cardoso and Sera, 1983). Some promising advanced selection genotypes with rust and bacterium resistant genes are available.

c) Leaf miner *(Perileucoptera Coffeella)*

The coffee leaf miner has recently become the main coffee pest, and the development of resistant cultivars is of extreme importance (Guerreiro et al. 2000). *C. stenophylla* and *C. racemosa* have the highest resistance levels among the *Coffea* species. Resistance is controlled by two dominant complementary genes in *C. racemosa* and two recessive genes in *C. stenophylla*. Some advanced selection tetraploid genotypes with leaf miner resistance derived from the natural hybridization between *C. racemosa* and *C. arabica* and backcrossed to develop *C. arabica* cultivars, are already available.

d) Fruit borer *(Hypotenemus hampei)*

Genotypes carrying qualitative or quantitative genes resistant to this pest must be identified to be used in integrated management. Alternatively, genes may come from other species and may be transformed genetically.

Cultivar adaptation to frosts

a) Cultivar recommendations by topography and exposure direction

There are two types of frosts, the white or irradiation frost which affects mainly coffee crops on lower land, and the black frost, also known as wind frost, which affects coffee crops mainly in high areas or on South facing slopes. Among the two available groups of cultivars, normal or tall and compact or low, tall cultivars are about 30% less susceptible to white frosts (Caramori and Sera, 1979) while low cultivars are about 30% less susceptible to black, or wind frosts (Figures 13 and 14). To optimize the use of the cultivars and reduce damage by 30%, tall cultivar planting is recommended on more prone to irradiation frost land and compact cultivars on wind frosts prone areas.

Table 5 - Development of IAPAR-59 cultivar, resistant to *Hemileia vastatrix* Berk et Br.

IAPAR 59 coffee was recommended for planting in 1993. Its main characteristic is its resistance to coffee rust, which eliminates the need for chemical fungicides in order to control the disease. This reduces costs and avoids environmental contamination.

IAPAR 59 is dwarf, thus it is ideal for high density planting and its yielding can be 25% higher than larger-sized cultivars. It belongs to the A physiological group: 94.9% of the plants are resistant to 30 races, 5.0% are resistant to 29 races and only 0.1% belongs to the E physiological susceptible group (Novo Mundo cultivar is classified in group E, for example). This characteristic reduces the annual yield potential in about 30 to 50% which is caused by rust and could increase up to 80% in favorable years to the disease. It also prevents quality loss, as leaf fall caused by the disease, good grain formation and reduces tree vigor.

PARENTALS: **"Timor Hybrid" CIFC832-2** **X** **Villa Sarchi CIFC971-10**

↓

F_1 GENERATION: **CIFC H361**

↓

F_2 GENERATION: **CIFC H361-4 = IAC1669**

↓

F_3 GENERATION: **IAC1669EP.127 C.506 = IAPARLF75163**

↓

F_4 GENERATION: **Regional Trials IAPARLF75163-1 to 24**

↓

F_5 GENERATION: **IAPARLF75163-22 = IAPAR-59**

Figure 13 - dwarf cultivar less damaged by the wind frost, June 1994.

Figure 14 - tall cultivar less damaged by the irradiation frost, July 2000

b) Cultivar management for fruit maturation

Another way to reduce frost damage through cultivar management is to reduce the risk of harvest loss from two years to one, which is achieved by avoiding planting late maturity cultivars in frost prone areas. Aqueous unripe or poorly developed fruits are more susceptible than leaves and, in case of frosts, late cultivars lose not only the next harvest productive branches but also the unripe fruits of the present season. This doubles the damage and renders coffee cultivation unsustainable Sera and Guerreiro(1998). Thus, planting earlier varieties may reduce frost loss to only one year, which would be equivalent to the normal loss due to the biennial production cycle (a smaller production following a large one) without frost, especially in intensive dense cultivation with high population of plants/ha.

c) Reduction of frost susceptibility by selection

The *C. racemosa* and *C. liberica* var. *dewevrei* species are 30% less susceptible to frost than the *C. arabica* (Agronomic Institute of Paraná Foundation, 1978). Transferring a significant portion of this quantitative resistance to *C. arabica* could reduce frost damage from severe to moderate, which would be sufficient for regions with frost occurrence transitions such as, for example, Northern Paraná, São Paulo, Southern Minas Gerais and Mato Grosso do Sul. Some advanced selection genotypes with compact architecture and rust resistance in the Catuaí x Icatu germplasm are less susceptible to frost than the "Catuaí" and the "Piatã" progenies [(*C. arabica* x *C. liberica* var. *dewevrei*) x Catuaí], and they have frost resistance similar to that of *C. liberica* var. *dewevrei.*

Examples of developed cultivars

Experimental cultivar IAPARLF 77054-40-10

Derived from the 'Catuaí' x 'Icatu' cross made at IAC in 1972. The material was introduced by IAPAR as IAC H 9878 – EP 187 c. 582 and classified as IAPAR 77054. Through the genealogical method, the progeny IAPAR 77054-40 was selected from the introduced materials and the IAPARLF 77054-40-10 progeny was later obtained. It is a medium-size plant, smaller than the 'Catuaí', with red fruits when ripe, and recommended for dense cropping in regions with low altitudes and sandy soils in Paraná. It has greater vigor, less annual yield oscillation than the 'Catuaí' and high grain/fruit ratio. Among the compact cultivars, it shows better adaptation to high temperatures, moderate frosts and poor soils. The IAPARLF 77054-40-10 progeny presents moderate resistance to the rust types currently identified in Paraná.

Root knot nematodes

Nematodes belonging to the *Meloidogyne* genus limit coffee production in infested areas. Areas infested with *M. incognita* (four physiological races), *M. paranaensis* and, in a less damaging degree, *M.exigua* require resistant root-stock and/or non-grafted resistant cultivars The Apoatã root-stock cultivar (C. canephora) was released with resistance to the root-knot nematodes *M. exigua* and *M. incognita* and recommended for planting in the state of São Paulo (Fazuoli, 1981; Fazuoli et al., 1983). It is also resistant to the M. paranaensis nematode in varying degrees.

Among the *C. arabica* genotypes, IAPAR-59 is completely resistant to *M. exigua in* Costa Rica (Bertrand, 1999), while IAC 4782-925, a "Icatu" derived lineage, show incomplete resistance to high *M. incognita* soil populations (Matiello et al. 1998). The advanced IAPAR LN94066 line derived from the "Catuaí" x "Icatu" cross shows quality, high yield and moderate resistance to *M. paranaensis* under high field population conditions (Sera et al., 2000).

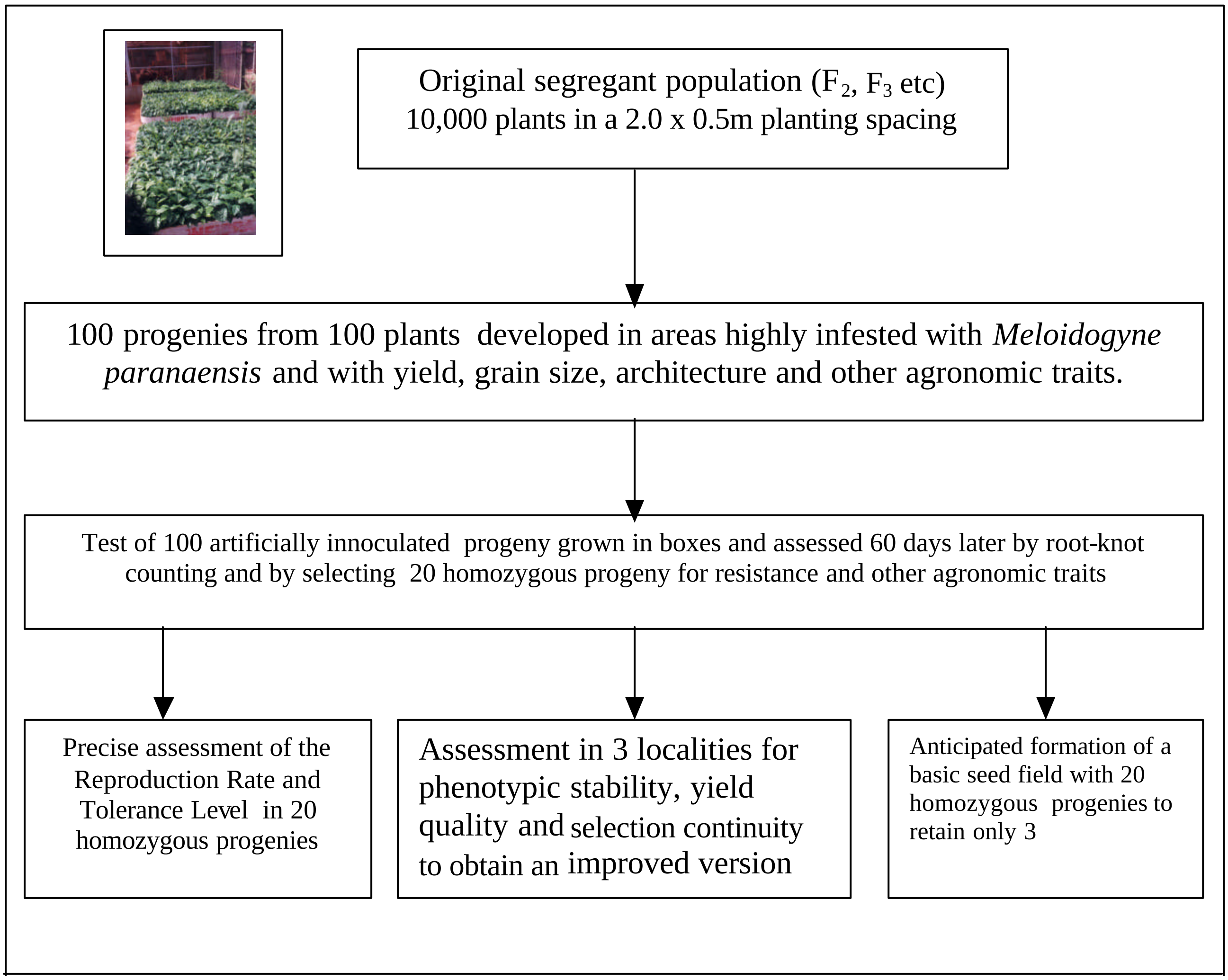
New *C. arabica* selections with large seeds and early fruit maturity are being developed as C. canephora root-stock cultivars which are resistant to all M. incognita physiologic races (races 1, 2, 3, and 4) and to *M. paranaensis.* Table 6 shows an example of a breeding scheme developed to obtain root-knot nematode resistant coffee cultivars.

Figure 15 - Left: Cultivar with moderate resistance to nematode *M. paranaensis* next to highly susceptible lineages. **Center**: Roots of moderately resistant cultivar at 5 years in highly infested areas. **Right**: Root system of highly susceptible lineages.

Example of cultivar development IAPARLF 77041-62-6-10 experimental cultivar

Belonging to the Catuaí Sh_2Sh_3 germplasm, it was obtained from a cross generated at IAC in 1971. It was introduced in Paraná by IAPAR as IAC H8721 – EP164c.1420 in 1977 and classified as IAPAR 77041. Through the genealogical method, the progeny IAPAR 77041-62 was selected from the introduced materials. After successive selection cycles, the IAPAR 77041-62-6 and IAPARLF 77041-62-6-10 F_6 progenies were obtained. Both show moderate resistance to the rust races currently identified in the state of Paraná. They are medium-size plants with red fruits when ripe and with moderate resistance to the *M. paranaensis* nematode. IAPARLF 77041-62-6-10 is recommended preferentially for areas which are highly exposed to wind frost in the warmer regions of Paraná, and for areas infested with the *M. paranaensis* nematode.

Table 6 - Assessment and juvenile selection scheme regarding resistance to *Meloidogyne paranaensis* nematode in the field and in the greenhouse together with the anticipated formation of a basic seed field, regional assessment and precise assessment for resistance and tolerance.



Experimental cultivar IAPARLN 93166-9

Originated from the introduction of the experiment carried out by the late Brazilian Coffee Institute (IBC): Plant 3 –1 of progeny 32 belonging to the Icatu germplasm. This material was taken to IAPAR that used the genealogical method to select the IAPARLN 93166-9 progeny in an area highly infested by *M. paranaensis*. IAPARLN 93166-9 is tall, susceptible to rust and show yellow fruits when ripe. It is outstanding in terms of uniform maturity, grows larger fruits than the ‘Acaiá’ and shows moderate resistance to *M. paranaensis*. It is preferentially recommended for areas exposed to irradiation frost in the warmer regions of the Paraná state infested with *M. paranaensis*.

FINAL CONSIDERATIONS

A coffee breeding strategic plan is vital and decisive for the success of any breeding program, and it requires some considerations. First of all, an in-depth knowledge of all aspects of the cropping systems and the origin and evolution of the *Coffea* species plus an understanding of consumer demands and global commercial competition is required to ensure that the work of a lifetime will bring good results. Any strategic mistake will be very frustrating since more than 20 years are usually spent from hybridization to successful cultivar release, and little time is left for redirecting the breeding program. Secondly, a careful diagnosis of the culture is fundamental to evaluate its problems and potentialities ensuring proper intervention on high priority issues. The breeding cycle, which limits the development of cultivars, can be greatly reduced from 20 to 10 years by changing some simple procedures in the cultivar development strategy and by aggregating new tools such as biotechnology, information and bio-statistics techniques. Finally, the genetic gain per year can be sharply increased with small additional investments in these research programs through the provision of qualified human resources, materials and adequate facilities.

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RESUMO

Melhoramento Genético do Café no IAPAR

O programa de pesquisa em melhoramento genético do cafeeiro, iniciada em 1973, está apresentado neste trabalho. As características de um programa de melhoramento de uma planta perene propagada por semente com ciclo bienal de produção e dificuldades em avaliar a longevidade produtiva e sua limitação principal do tempo gasto no desenvolvimento e liberação de cultivares para o plantio comercial são apresentadas. O diagnóstico sucinto da cultura de café arábico na região e as prioridades e estratégia de desenvolvimento e manejo de cultivares dentro da tecnologia de produção "Modelo IAPAR de café adensado" são detalhados. Os avanços obtidos no desenvolvimento e manejo de cultivares com as outras tecnologias para os principais problemas são discutidos. É proposto um conjunto de alternativas, técnicas, métodos, procedimentos e estratégias para reduzir o tempo gasto no desenvolvimento de cultivares de café em 12 anos ao invés de 24 anos.

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