

UNIVERSIDADE ESTADUAL PAULISTA – UNESP

CAMPUS DE JABOTICABAL

**MODELOS AGROMETEOROLÓGICOS PARA PREVISÃO DA
PRODUTIVIDADE E QUALIDADE DE BEBIDA NATURAL DO
CAFEEIRO**

Lucas Eduardo de Oliveira Aparecido

Engenheiro Agrônomo

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Lucas Eduardo de Oliveira Aparecido

Orientador: Prof. Dr. Glauco de Souza Rolim

Dissertação apresentada à Faculdade de Ciências Agrárias e Veterinárias – Unesp, Câmpus de Jaboticabal, como parte das exigências para a obtenção do título de Mestre em Agronomia (Produção Vegetal)

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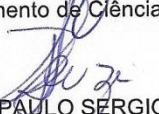
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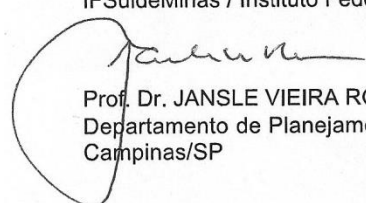
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“Se soubéssemos o que era aquilo que estávamos fazendo, não seria chamado de
pesquisa”

Einstein, A.

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A Deus, o grande doutor da vida.

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MODELOS AGROMETEOROLÓGICOS PARA PREVISÃO DA PRODUTIVIDADE E QUALIDADE DE BEBIDA NATURAL DO CAFEEIRO

RESUMO – A previsão da produtividade dos cultivos, através de modelos agrometeorológicos, são técnicas estratégicas robustas para a realização do planejamento, uma vez que o conhecimento prévio das safras agrícolas facilitam as tomadas de decisões. A previsão em modelagem, diferentemente de estimação, é determinar a partir de dados atuais uma condição futura, como por exemplo a produtividade e a qualidade de produtos agrícolas. Objetivou-se desenvolver e ajustar modelos agrometeorológicos para a previsão da produtividade e qualidade de bebida do cafeeiro para o Estado de Minas Gerais. Foram utilizados na previsão os elementos meteorológicos mensais das localidades do Sul de Minas: Guaxupé, Monte Santo de Minas e São Sebastião do Paraíso e do Cerrado Mineiro: Coromandel, Serra do Salitre e Tiros. Os modelos foram construídos com regressão linear múltipla, visando maximizar a antecipação da previsão. A variável dependente foi à produtividade de cada localidade, enquanto que, as variáveis independentes foram os elementos meteorológicos mensais do período de 1997 a 2014. Os elementos utilizados foram à temperatura do ar (°C), a precipitação pluviométrica (mm), a evapotranspiração potencial (mm), o armazenamento de água no solo (mm), a deficiência hídrica (mm) e o excedente hídrico (mm). Os modelos agrometeorológicos foram classificados buscando a minimização do erro percentual absoluto médio (MAPE) e o aumento do coeficiente de determinação ajustado (R^2 ajustado). Os modelos agrometeorológicos desenvolvidos em função dos elementos meteorológicos foram acurados para todas as regiões, pois o maior MAPE foi de 3.13% e 2.82% em São Sebastião do Paraíso e Tiros, respectivamente. As menores previsões foram de seis e cinco meses para as localidades de Guaxupé e Coromandel, respectivamente. As faixas de valores mensais para cada elemento meteorológico indicam que para ocorrência de alta qualidade de bebida é necessário temperaturas do ar mais elevadas no Cerrado, menores precipitações, menores armazenamentos e maiores deficiências hídricas quando comparados com ao Sul de Minas Gerais.

Palavras-Chave: modelagem, *Coffea arabica* L., agrometeorologia, clima.

AGROMETEOROLOGICAL MODELS FOR FORECASTING YIELD AND NATURAL COFFEE DRINK QUALITY

ABSTRACT – The agrometeorological models for crop yield forecasting are robust for strategic planning techniques, since, prior knowledge of agriculture crops facilitate decision making. The forecasting, different from estimation, is from actual data determine a future condition, such as yields, phenology duration and quality of agricultural products. This work aimed to develop and adjust agrometeorological models to forecast yield and coffee natural drink quality for State of Minas Gerais. We forecasted yields as functions of monthly meteorological variables for three locations in the southern region of the state of Minas Gerais, i.e. Guaxupé, Monte Santo de Minas, and São Sebastião do Paraíso, and for three locations in the Cerrado Mineiro region of Minas Gerais, i.e. Coromandel, Serra do Salitre and Tiros. We used multiple linear regressions selecting independent variables (IV) trying to maximize the anticipation of the yield forecasting for each locality. The IV were the monthly weather elements from 1997 to 2014. The elements used were the air temperature (°C) rainfall (mm), the potential evapotranspiration (mm), the water storage in the soil (mm), the water deficit (mm) and the water surplus (mm). The selection of IV was made testing all possible combinations (APC), avoiding multicollinearity. The models were built with multiple linear regression to maximize the anticipation of forecast. The better models were classified seeking to minimize the mean absolute percentage error (MAPE), determination coefficient (adjusted R^2) near 1 and selecting model only with significance at 0.01. The agrometeorological models were accurate for all regions and the lower anticipation period were six and five months for the locations of Guaxupé and Coromandel, respectively. Ranges of monthly values for each meteorological element were established indicating that to reach a high quality of drink at Cerrado it is necessary higher temperatures, lower precipitations, lower storages and higher water deficits when compared to the South of Minas Gerais.

Key Words: modelling, *Coffea arabica* L., agrometeorology, climate.

CAPÍTULO 1 - Considerações Gerais

Introdução

O café é cultivado em vários países e o Brasil tem a maior produção de café do mundo. O café é uma atividade agrícola brasileira de importância indiscutível, sendo um dos principais produtos agrícolas de exportação, agregando considerável volume de recursos à balança comercial. O cafeeiro arábica é fortemente afetado nos seus diversos estádios fenológicos pelas condições meteorológicas, uma vez que o clima influencia a bienalidade produtiva e a qualidade da bebida.

A variabilidade climática proporciona uma grande variação nas atividades agrícolas, sendo um dos principais fatores responsáveis pelas oscilações da quantidade produzida de café. Dentre os elementos meteorológicos de importância no cultivo cafeeiro, destacam-se a temperatura do ar, a radiação solar e a precipitação pluviométrica.

A melhor forma de sintetizar quantitativamente os efeitos das condições climáticas no desenvolvimento, produtividade e qualidade da bebida do café é por meio de modelos de cultivos. Com a utilização dos modelos agrometeorológicos consegue-se conhecer previamente as safras agrícolas, através das previsões pelos modelos, sendo considerada uma questão estratégica nos processos de planejamento.

Todavia, são escassos os modelos agrometeorológicos que realizam o processo de previsão, uma vez que, grande parte dos modelos realizam apenas as estimativas de produtividade. De maneira conceitual, a previsão nada mais é do que quantificar um evento futuro utilizando-se de dados disponíveis atuais. Enquanto que, o processo de estimação é a quantificação de um fenômeno atual a partir de dados atuais.

A qualidade natural do cafeeiro é fortemente influenciada pelas condições climáticas. Quando o clima não é favorável no período de enchimento de grãos, o acúmulo de fotoassimilados não é bem sucedido, reduzindo neste ano a qualidade da bebida do cafeeiro. A temperatura do ar e as condições hídricas são fatores limitantes a qualidade da bebida.

Na literatura não foram encontrados trabalhos para previsão da produtividade e qualidade de bebida. Assim, objetivou-se desenvolver e validar modelos agrometeorológicos estatísticos para previsão mais antecipada possível de produtividade anual e qualidade de bebida do cafeeiro para regiões do Estado de Minas Gerais, além de aumentar o conhecimento das relações dos elementos meteorológicos mensais normais com a qualidade de bebida natural do cafeeiro arábica e identificar faixas de valores dos elementos meteorológicos que otimizem a qualidade.

Revisão de Literatura

O café é o principal cultivo de vários países (RODRIGUES et al., 2013). Na atividade agrícola brasileira sua importância socioeconômica é indiscutível (RESENDE et al., 2009; FERREIRA Jr et al., 2016), pois, é um dos principais produtos agrícolas de exportação, uma vez que agrega considerável volume de recursos a balança comercial. O café apresenta várias propriedades funcionas de qualidade, como a cafeína, aminoácidos, minerais e compostos fenólicos, sendo a bebida mais consumida no mundo (BUTT; SULTAN, 2011; KITZBERGER et al., 2013).

O cafeeiro é uma planta perene, pertencente à família Rubiaceae (CUBRY et al., 2013). Mundialmente, as duas espécies economicamente mais importantes de café são o *Coffea arabica* L. e *Coffea canephora* Pierre (BRAVO-MONROY et al., 2016), representando 74,92% e 25,08% da produção mundial, respectivamente (CONAB, 2015). O *Coffea arabica* (café arábica) é de alta qualidade, e constitui mais de 60% de toda produção mundial, já o *Coffea canephora* (café Robusta) é de qualidade relativamente baixa em comparação com Arábica (BRAVO-MONROY et al., 2016).

As áreas de produção brasileira se distribuem na região centro-sul, principalmente nos estados de Minas Gerais, São Paulo, Espírito Santo e Paraná (ANDRADE et al., 2012). O estado de Minas Gerais apresenta em torno de 6,9% da área total do Brasil e se destaca como maior produtor de café do país, com uma participação em torno de 51% de todo café produzido no Brasil (BARBOSA et al.,

2012).

O cafeeiro arábico é um cultivo que necessita de dois anos para completar seu ciclo fenológico. O período vegetativo ocorre no primeiro ano e o processo de reprodução no segundo. No desenvolvimento vegetativo ocorre à formação e o crescimento dos ramos vegetativos, como as gemas axilares nos nós, esse processo ocorre em fotoperíodo de dias longos. Com a redução do fotoperíodo as gemas vegetativas axilares são induzidas por fotoperiodismo em gemas reprodutivas. O período produtivo inicia-se com a florada que precede a formação dos chumbinhos. Em agosto inicia-se a expansão e a formação dos grãos que ocorre até atingir o tamanho normal, posteriormente ocorre a granação e a maturação dos frutos (CAMARGO; CAMARGO, 2001). De maneira geral, os estádios fenológicos do cafeeiro é dividido em 11 fases (Figura 1).



Figura 1. Determinação de estádios fenológicos do café arábica (PEZZOPANE et al., 2003).

A variabilidade climática causa forte impacto nas atividades agrícolas (SÁ JUNIOR et al., 2012) sendo o principal fator responsável pelas flutuações e

oscilações da produtividade de grãos de café (CAMARGO, 2010). Hoogenboom (2000) salienta que os elementos meteorológicos críticos para a produção agrícola são normalmente a temperatura do ar, a radiação solar e a precipitação. Para o cafeeiro, Camargo (2010) relata que a variação do fotoperíodo e a distribuição pluviométrica são elementos que proporcionam maior interferência na fenologia do cafeeiro, e conseqüentemente, acondicionam a produtividade e qualidade dos grãos do cultivo.

O cultivo do cafeeiro arábica é fortemente afetado nos seus diversos estádios fenológicos pelas condições meteorológicas interferindo fortemente na bienalidade produtiva, na qualidade do produto e na sustentabilidade da planta (PICINI et al., 1999). As condições climáticas também influenciam na pós-colheita do cafeeiro, uma vez que, em regiões de clima quente que apresentam elevados índices de radiação solar o tempo de secagem em terreiros de concreto é menor (RESENDE et al., 2009).

A radiação solar provê a energia para a fotossíntese afetando a partição de carboidratos e o crescimento dos componentes individuais da planta, além determinar sua transpiração (OLIVEIRA et al., 2012), para Angelocci et al. (2008) a radiação solar é uma importante variável meteorológica, uma vez que, origina o processo de transpiração e a fotossíntese, carecendo ser avaliada e mais bem estudada.

A temperatura do ar regula a taxa de desenvolvimento vegetativo e reprodutivo, e segundo Camargo e Pereira (1994) temperaturas do ar elevadas, associadas ao déficit hídrico durante a florada, podem causar abortamento das flores (PEREIRA et al., 2008), sendo, que a exposição continua a temperaturas acima de 30°C resultam no amarelecimento das folhas e na redução do crescimento (DAMATTA; RAMALHO, 2006).

A seca afeta a evapotranspiração, a extração de umidade das raízes, a distribuição do sistema radicular e o tamanho do dossel (APARECIDO et al., 2015), dessa forma afetando as taxas de desenvolvimento das plantas. O cafeeiro em sequeiro, a deficiência hídrica é responsável pela queda de produção (CARVALHO et al., 2011), já que, a disponibilidade hídrica é um dos principais condicionantes da produtividade econômica dos cultivos (PICINI et al., 1999). O cafeeiro, após a

fecundação, se apresenta na formação chumbinhos, neste estágio uma estiagem forte, o estresse hídrico poderá prejudicar o crescimento dos frutos (CAMARGO, 2010).

Para Hoogenboom (2000) a temperatura da superfície do solo é importante para taxas de germinação. A umidade relativa, a temperatura do ponto de orvalho e o déficit de pressão de vapor interferem na presença e atividade de pragas e doenças, e o vento afeta a taxa transpiratória das plantas e disseminação de insetos e doenças. Grande parte desses processos pode ser simulada por modelos agrometeorológicos (ROLIM et al., 2008).

A representação matemática simplificada de um sistema é conhecida como modelo, enquanto que o processo de desenvolvimento deste é chamado modelagem (JONES et al., 1987). A melhor forma de sintetizar quantitativamente os efeitos das condições climáticas no desenvolvimento, produtividade e qualidade da bebida do café é por meio de modelos de cultivos. Esses modelos ponderam os efeitos dos elementos meteorológicos na produtividade dos cultivos, quantificando principalmente esses efeitos durante os períodos fenológicos críticos, no caso do cafeeiro, a floração, a formação, o crescimento e a maturação dos frutos (NUNES et al., 2010).

Os modelos integram conhecimentos das áreas de agrometeorologia, sensoriamento remoto, fisiologia vegetal, fitotecnia, ciência do solo e economia de forma interdisciplinar, podendo realizar estimativas (JAME; CUTFORTH, 1996) e previsões (GOURANGA; ASHWANI, 2014) da produtividade, auxiliando na estratégia e tomadas de decisões nas cadeias produtivas, além de realizar simulações acuradas da dinâmica do crescimento de cultivos (JAME; CUTFORTH, 1996).

Com a utilização dos modelos agrometeorológicos consegue-se conhecer previamente as safras agrícolas, através das previsões por modelos, sendo considerada uma questão de estratégia no momento do planejamento (SANTOS; CAMARGO, 2006).

Os dois tipos de modelos mais utilizados são os estatísticos conhecidos como modelos funcionais “empíricos” (MONTEITH, 1996) e os modelos mecanísticos. Os modelos estatísticos são essencialmente práticos, baseado em análises de

regressões, e visão estimar o desenvolvimento dos cultivos (PASSIOURA, 1973), geralmente utilizam às condições de precipitação pluviométrica, temperatura do ar ou disponibilidade hídrica do solo de períodos do ciclo do cultivo como variáveis independentes e a produtividade do cultivo como variável dependente (ROBERTSON, 1983), cujos coeficientes de ponderação se obtêm normalmente pela análise de regressão múltipla (CARVALHO et al., 2004).

Os modelos mecanísticos são complexos, estabelecendo relações de causa e efeito entre o ambiente e os cultivos (PASSIOURA, 1973), visão interpretação quantitativa e qualitativa do sistema (JONES et al., 1986), apresentam forte embasamento físico e biológico com os processos de desenvolvimento das plantas (JAME; CUTFORTH, 1996).

Entretanto, são poucos os modelos agrometeorológicos que trabalham no processo de previsão, uma vez que, a maioria dos modelos lidam apenas com as estimativas de produtividade. A previsão é o processo de quantificação de um evento futuro a partir de dados disponíveis atuais. Por sua vez, o processo de estimação é a quantificação de um fenômeno atual a partir de dados atuais (ROLIM et al., 2008).

Os modelos agrometeorológicos além de realizar a previsão e/ou estimação ainda relaciona as condições ambientais, como a temperatura do ar e disponibilidade hídrica no solo, com a fenologia e produtividade do cultivo do cafeeiro (NUNES et al., 2010).

Camargo et al. (1988) desenvolveram modelos agrometeorológicos baseados em Doorenbos e Kassam (1979) para estimar a produtividade potencial da soja no Estado de São Paulo, além de definir a produtividade potencial de diversas cultivares, levando em conta a época de semeadura. Por sua vez, Picini et al., (1999) estimando a produtividade do café observaram que a produtividade do cultivo do ano anterior é uma variável deve ser considerada em modelos agrometeorológicos, uma vez que o ciclo bienal interfere sobre o efeito das condições meteorológicas.

Camargo e Camargo (2001) buscaram estimar o início do período de maturação do cafeeiro, definindo e esquematizando as fases fenológicas, e por fim, propuseram a uma forma racional constituída de seis fases distintas

envolvendo os dois anos fenológicos, iniciados em setembro. Enquanto que, Favarin et al. (2002) desenvolveram modelo matemáticos simples para estimativa do índice de área foliar, e verificaram que área lateral do dossel, a altura e o diâmetro da seção inferior do dossel, podem ser usados na estimativa do índice de área foliar.

Carvalho et al. (2004) trabalhando com modelos de regressão para a estimação da produtividade de cafeeiros em Minas Gerais, concluíram que o comportamento de variação das produtividades estimadas pelo modelo acompanha a variação das produtividades observadas. Carvalho et al. (2005) desenvolveu um modelo de estimação da produtividade para o café, em sete municípios do Estado de Minas Gerais, porém, o modelo se mostrou inconsistente, apresentando erros das estimativas bastante discrepantes, evidenciando a complexidade de modelagem de cafezais.

Pezzopane et al. (2003) desenvolveram uma escala, avaliando o desenvolvimento de estádios fenológicos do cafeeiro arábica, utilizando-se fotografias, de diversos estágios como, período reprodutivo, compreendidas entre o estágio de gemas dormentes e o de grão seco, a escala se mostrou útil para estudos possibilitando a identificação de variáveis climáticas relacionadas ao desenvolvimento. Também trabalhando com a escala fenológica do cafeeiro, Morais et al. (2008) realizaram o detalhamento da fase reprodutiva do cafeeiro arábica, e alegaram que a escala proposta pode subsidiar estudos de crescimento, produtividade e manejo da lavoura cafeeira.

Santos e Camargo (2006) modificaram e parametrizaram um modelo matemático que estimasse a quebra de produtividade, do cultivo do cafeeiro arábica, para Estado de São Paulo. Os autores concluíram que o modelo proposto parametrizado tem potencial para estimar a produtividade do café, podendo servir como subsídio aos trabalhos de previsão de safra. Por sua vez, Zacharias, Camargo e Fazuoli, (2008) parametrizaram e validaram um modelo agrometeorológico de estimativa do início da floração plena do cafeeiro arábica no Estado de São Paulo, ao final, observaram que o modelo considera os valores acumulados de 335 mm de evapotranspiração potencial ou 1579 graus-dia, para que as gemas florais atinjam a maturação.

Pezzopane et al. (2008) procuraram estimar o período entre o florescimento e o final de maturação do café arábica cv. Mundo Novo, levando-se em conta a temperatura basal inferior, a soma térmica e o acúmulo da evapotranspiração de referência (ETP), e notaram que o acúmulo médio de ETP foi de 761 mm, para o período florescimento-colheita, e os valores de temperatura-base e soma térmica, foram 10,2°C e 2887 graus-dia sem correção do fator hídrico e 10,5°C e 2761 graus-dia com a correção.

Oliveira et al. (2012) propôs um modelo para recomendar a orientação adequada das linhas de cafeeiro na implantação, o modelo proposto estimou a orientação de -24° 16' como sendo a melhor para o plantio das linhas de cafeeiro. Trabalhando com o método da Zona Agroecológica (ZAE) Oliveira et al. (2012) parametrizaram, calibraram e testaram um modelo estimando a produtividade do cultivo da cana de açúcar, para o Estado de Minas Gerais, e ao final concluíram que adaptação realizada no método da Zona Agroecológica permitiu estimar adequadamente os valores de produtividade da cultura da cana-de-açúcar.

Rodrigues et al. (2011) generalizaram um modelo para capturar o crescimento e o desenvolvimento do café, de acordo com as condições climáticas encontradas na Colômbia e Brasil e relataram que o modelo representa fielmente os dados de campo e podem ajudar no desenvolvimento de estratégias de gestão e avaliação econômica. O mesmo autor, Rodrigues et al. (2013) desenvolveram um segundo modelo acrescentando variáveis relacionadas ao fruto do cafeeiro e a broca do café, e observaram grande importância de alguns dados como, padrão de emergência, competição intra-específica e chuva, porém, as previsões foram favoráveis comparados para os dados de campo, utilizando variáveis climáticas de entrada.

Cunha e Volpe (2011) estudando o cafeeiro cv. Obatã desenvolveram modelos correlacionando massa seca versus massa fresca e a massa fresca e seca em função de dias após florescimento. Ao final, concluíram que o modelo sigmoidal representou o crescimento do fruto do cafeeiro em massa fresca e/ou seca em função de dias após a florada. Por sua vez, Rosa et al. (2010) estimaram a produtividade do cafeeiro com modelo agrometeorológica-espectral e observou que

o método foi eficaz para estimar a produtividade dos cafezais quanto o modelo oficial do IBGE, sendo possível espacializar a quebra de produtividade e estimar 80% da produtividade final na primeira quinzena de fevereiro, antes do início da colheita.

Todos os trabalhos citados basicamente realizam estimações. Existem algumas técnicas que utilizam modelos de cultivos para fins de previsão. Uma opção usual na literatura é a utilização de modelos meteorológicos de previsão de circulação geral da atmosfera associados a modelos de cultivo. Os trabalhos de Hansen e Indeje (2004) e Stone e Meinke (2005) são exemplos desta linha de pesquisa.

Na literatura também foram encontradas outras formas, como a associação de modelos de previsão de fenômenos ENSO (El niño e La niña) com os modelos de cultivo. Usando esta metodologia pode-se citar os trabalhos de Hansen, Potgieterb e Tippetta (2004) e Jones et al. (2000) que realizam as previsões antecipadas de produtividade de milho na Austrália e de trigo no Sul dos Estados Unidos, respectivamente.

Por fim, existem trabalhos de previsão de produtividade feitos com base probabilística usando modelos estatísticos diversos. Por exemplo, pode-se citar o trabalho de Mkhabela et al. (2005) que realizaram a previsão da produtividade do milho 2 meses antes da colheita no Sudeste da África. Savin et al. (2007) que trabalhando com redes neurais conseguiram prever a produtividade final de trigo já durante o período de florescimento com 74% de acurácia na Rússia. Keong e Keng (2012) utilizando modelos de regressão linear múltipla, com seleção de variáveis pelo método stepwise, obtiveram previsão do rendimento de óleo da Palma com 9 meses antes da colheita na Malásia. E finalmente Gouranga e Ashwani (2014) que realizaram a previsão da produtividade do arroz com 30 dias de antecedência da colheita na Índia.

Em relação qualidade de bebida natural do cafeeiro. O Brasil, particularmente nos Estados de Minas Gerais e São Paulo, normalmente a secagem dos grãos do cafeeiro ainda com casca é feita em terreiros pela ação do sol, somente após esta etapa esses grãos são descascados, beneficiados e enviados a cooperativas. Este processo facilmente pode promover a diminuição da qualidade da bebida devido à

fermentação na mucilagem por meio da ação de bactérias. Entretanto, quando esse processamento pós-colheita é bem feito promove o aparecimento de sabores exóticos na qualidade de bebida com características regionais bem distintas (MARTINS et al., 2015).

Tratamentos pós-colheita constituem basicamente a separação de grãos cereja dos imaturos e verdes, secagem, descascamento e torra dos grãos em temperaturas e duração variadas (FAVARIN et al., 2004; BORÉM et al., 2008). Outro tratamento pós-colheita é o armazenamento dos grãos que deve ser o mais breve possível visando a manutenção da qualidade dos frutos, evitando assim o aumento dos ácidos graxos linoleico e palmítico e o branqueamento dos grãos (CORADI et al., 2007).

Quando as condições climáticas não são favoráveis, o processo de acúmulo de fotoassimilados é desfavorecido, condicionando uma diminuição da qualidade de bebida (FAGAN et al., 2011). Brando e Staut (2012) relatam que a produção do café arábica de alta qualidade é considerada tão difícil quanto a produção de vinhos exclusivos, uma vez que não depende somente da experiência dos produtores no decorrer do ano, mas também das características climáticas predominantes na região.

A baixa disponibilidade hídrica durante o enchimento dos grãos também favorecem a má formação dos grãos diminuindo sua qualidade natural de bebida (FAGAN et al., 2011). O excesso de precipitações pluviométricas durante a maturação promove o aumento da umidade do ar, colaborando com a proliferação de microrganismos que podem provocar a fermentação da polpa dos grãos, reduzindo drasticamente a qualidade natural de bebida do cafeeiro (ABRAHÃO et al., 2009).

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CAPÍTULO 2 – Forecasting annual yield of *Coffea arabica* L. using monthly water deficiency

ABSTRACT - Estimation in science is the use of actual data to simulate an actual process, and forecasting is the use of actual data to simulate a future process or event. The forecast is the vanguard in the modelling of crops. We developed regional statistical agrometeorological models to forecast annual yields of *Coffea arabica* L. in the two most important coffee regions in Brazil. We forecasted yields as functions of monthly water deficits for three locations in the southern region of the state of Minas Gerais, i.e. Guaxupé, Monte Santo de Minas, and São Sebastião do Paraíso, and for three locations in the Cerrado Mineiro region of Minas Gerais, i.e. Coromandel, Serra do Salitre and Tiros. We used a meteorological data set spanning 18 years and multiple linear regression for model construction. The models were calibrated in seasons of high and low-yields due to the inherently high biennial yields in Brazil. Brazilian coffee is produced in unshaded areas, differently from the highlands of Ethiopia. The high amount of solar radiation strongly promotes biennial crop production: the trees develop vegetatively one year and produce beans the next. All models calibrated for high- and low-yield seasons were significant at 0.05 and accurate, with mean absolute percentage errors $\leq 2.9\%$. The minimum forecasting period for yield was six months for southern Minas Gerais and Cerrado Mineiro. Water deficits had a larger influence during the reproductive stage (second year) in high-yield seasons and during the vegetative stage (first year) in low-yield seasons.

Key Words: Model; Water balance; Prediction; Climate; Agrometeorology.

Introduction

Forecasting, which differs from estimation, is the quantification of a future event from currently available data. Estimation is the quantification of an actual event from current data (Rolim et al., 2008). Brazil is the world's largest coffee producer (Amarasinghe et al., 2015; Bravo-Monroy et al., 2016), and few studies have

forecasted yields as functions of the climatic conditions (Rodrigues et al., 2013a). Coffee is the most valuable tropical export product in the world (Craparo et al., 2015) and is the most consumed drink worldwide (Kitzberger et al., 2013; Zelber-Sagi et al., 2015).

Agriculture is an economic activity that is highly dependent on weather conditions (Ahmed et al., 2013; Aparecido et al., 2015). Coffee production and bean quality are highly sensitive to changes in microclimatic parameters (Craparo et al., 2015), mainly those related to water availability. Water deficits (DEFs) reduce crop yields (Khamssi et al., 2011) by affecting vegetative growth (DaMatta, 2004; Sakai et al., 2015). DEF was defined by Thornthwaite and Mather (1955) as the lack of evapotranspiration relative to a maximum (potential) theoretical value, it is determined as $DEF = PET - AET$, where PET is potential evapotranspiration, and AET is actual evapotranspiration estimated as a function of available water in the soil.

DEFs affect the amount of moisture extracted by roots, the spatial distribution of the root system, canopy size, and fruit growth of coffee plants (Amarasinghe et al., 2015). Reductions in coffee yield are mostly due to DEFs (Carvalho et al., 2011), because water stress after fertilisation affects fruit growth (Camargo, 2010). The effects of climate on crop yields can be evaluated with crop models (Vianna and Sentelhas, 2014; Shao et al., 2015). These models can help farmers to make decisions for achieving sustainable agriculture (Syversten and Garcia-Sanchez, 2014).

Models collect information from agrometeorology, remote sensing, plant physiology, plant science, soil science, and economics in an interdisciplinary way for predicting yields (Jame and Cutforth, 1996) and for forecasting (Gouranga and Ashwani, 2014). The models can also assist strategies of production (Chipanshi et al., 2015) by simulating the dynamics of crop growth (Pinto et al., 2015).

Several models have been published that estimate coffee yield. For example, Santos and Camargo (2006) developed a mathematical model to estimate yield losses of arabica coffee in the state of São Paulo. Carvalho et al. (2004) developed a model for estimating coffee yield in Minas Gerais, but the model was inconsistent, with highly discrepant estimate errors, highlighting the complexity of coffee modelling. Rosa et al. (2010) estimated coffee yield effectively with an agrometeorological-

spectral model, with which could spatialise the yield.

Studies of forecasting, however, are rare. Some studies have a probabilistic basis in the statistical models. For example, Savin et al. (2007) forecasted wheat yield in Russia with an accuracy of 74%. Keong and Keng (2012) forecasted the yield of palm oil in Malaysia nine months before the harvest using multiple linear regression models and stepwise variable selection. Gouranga and Ashwani (2014) forecasted rice yields in India 30 days before the harvest. Finally, Moreto and Rolim (2015) forecasted the yield and quality of Valência oranges six months before harvesting. No model, however, has yet been developed to forecast the yield of arabica coffee.

This study aimed to develop agrometeorological models for forecasting annual yields of *Coffea arabica* L. as functions of monthly DEFs during the coffee cycle for six important locations in Minas Gerais, Brazil: Guaxupé (GXP), Monte Santo de Minas (MSM), São Sebastião do Paraíso (SSP), Coromandel (CRD), Serra do Salitre (SDS), and Tiros (TRS).

Materials and Methods

We used a historical series of climatic and phytotechnical data for coffee crops in Minas Gerais. Brazil's largest coffee producer (Ronchi et al., 2015). Representative locations of coffee production used for modelling were GXP, MSM, and SSP in the southern region of the state (SO_{MG}) and CRD, SDS, and TRS in the Cerrado Mineiro region (CE_{MG}) (Table 1 and Fig 1).

Table 1. Geographic and climatic description of the regions.

Regions	C/T ¹	Latitude	Longitude	Altitude (m)	Climate ²
South of Minas Gerais					
Guaxupé	C	21° 18' 13" S	46° 42' 31" W	824	B ₂ rB' ₄ a'
Monte Santo de Minas	C	21° 11' 44" S	46° 57' 46" W	892	B ₃ rB' ₃ a'
São Sebastião do Paraíso	C/T	20° 54' 36" S	47° 06' 34" W	973	B ₄ rB' ₂ a'
Cerrado Mineiro					
Coromandel	C	18° 28' 19" S	47° 11' 34" W	928	B ₂ wB' ₃ a'
Serra do Salitre	C	19° 05' 50" S	46° 40' 25" W	1244	B ₂ wB' ₃ a'
Tiros	C/T	18° 59' 53" S	45° 58' 11" W	977	B ₂ wB' ₃ a'

¹C and T is calibration and test, respectively; ²Following Thornthwaite climatic classification (1948).

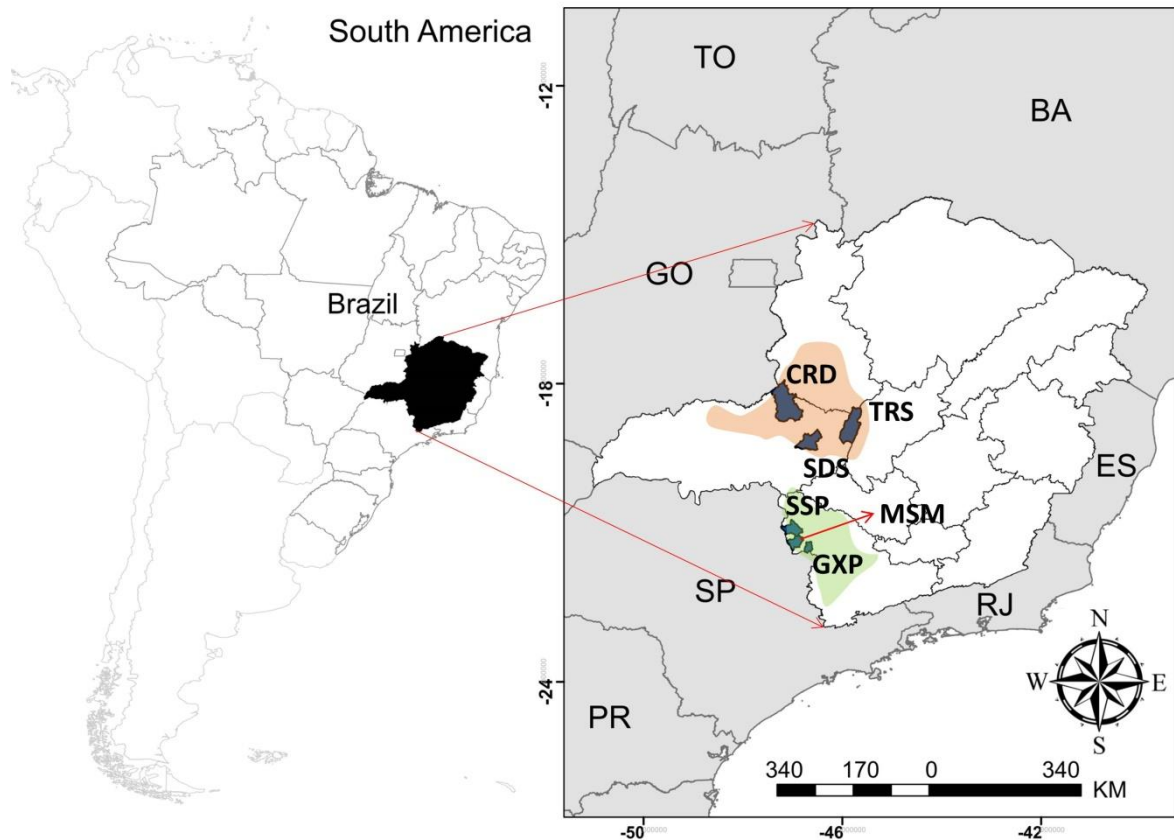


Fig 1. Main regions in the state of Minas Gerais, Brazil, for coffee production in Brazil: 1) Southern of Minas Gerais = GXP is Guaxupé, MSM is Monte Santo de Minas and, SSP is São Sebastião do Paraíso; 2) Cerrado Mineiro = CRD is Coromandel, SDS is Serra do Salitre and, TRS is Tiros.

Daily climatic data for these locations were obtained for 1997-2014 from Campbell CR21X (Campbell Scientific, Inc. Logan Utah, USA) automatic weather stations containing sensors for rainfall (Rain Gauge CR1000) and air temperature (HMP50-L). Daily rainfall data and minimum, average, and maximum temperatures were arranged on a monthly basis for calculating the potential evapotranspiration, using the model proposed by Camargo (1971) (equation 1). This model is similar to Thornthwaite (1948) for tropical regions (Camargo and Sentelhas, 1997).

$$PET = 0,01 \times Q_o \times T \times ND \quad (1)$$

where Q_o is daily solar atmospheric irradiance (mm day^{-1}), T is mean air temperature ($^{\circ}\text{C}$), and ND is number of days.

AET was calculated following Thornthwaite and Mather (1955) model (equation 2) at a monthly scale with a soil available water capacity of 100 mm:

$$ALT_i = STO_i - STO_{i-1}$$

$$AET = \begin{cases} R + |ALT| & , \text{if } ALT < 0 \\ PET & , \text{if } ALT \geq 0 \end{cases} \quad (2)$$

where STO is soil water storage; R is rainfall (mm); PET is potential evapotranspiration (mm), AET is actual evapotranspiration (mm), i is data from the current period and, $i-1$ is data from the previous period.

The coffee cycle begins with the development of the root system induced by dormancy of the aerial part of the plant. The development of the root system is intense during this period (Fig 2). Roots grow throughout the plant cycle, but growth is intensified when water is abundant (Larcher, 2004). Water deficits in tropical climates usually occur in the winter seasons.

The phenological cycle of *Coffea arabica* L. requires two years to complete. The growing season occurs in the first year, and reproduction occurs in the second year. Vegetative branches form and grow in the year of vegetative development ($y-1$) occurs the formation and growth of vegetative branches, and the number of axillary buds at the nodes, stimulated by a long photoperiods (Camargo and Camargo, 2001). The axillary vegetative buds then develop into reproductive buds with shorter photoperiods. The productive year (y) begins with flowering, the fertilised flowers lose their petals forming small round structures called “pinheads” that begin to expand in November into beans until March, and the fruit then matures and is harvested until July (Fig 2).

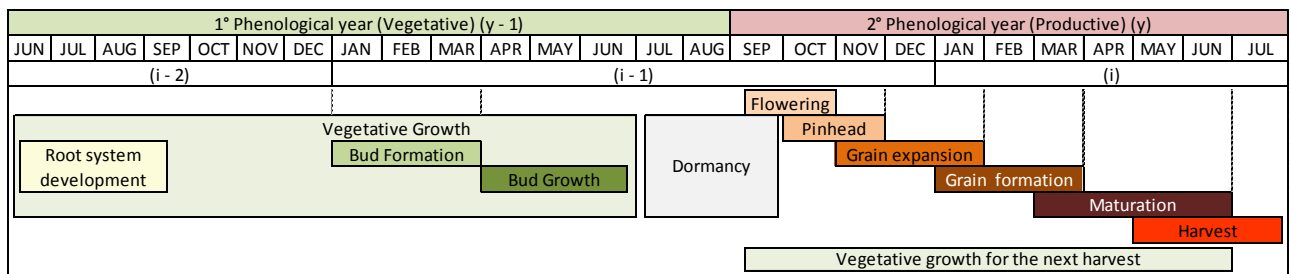


Fig 2. Phenology of the *Coffea arabica* L. crop (modified from Camargo and Camargo, 2001). Indexes = $y-1$ is first phenological year, y is second phenological year, $i-2$ is first chronological year, $i-1$ is second chronological year and i is third chronological year.

We used multiple linear regressions to model coffee yield for forecasting (Equation 3). Monthly DEF data for the two years of the coffee phenological cycle were the independent meteorological variables used in the construction of the models. Months without deficits or variations were removed from the analysis.

$$Y = a \times X_1 + b \times X_2 + c \times X_3 + \dots + CL \quad (3)$$

where Y is yield in sacks ha⁻¹; a, b, c, ... are adjusted coefficients (weight); X₁, X₂, X₃, ... are selected monthly DEFs from the two phenological years of the coffee crop; and CL is the linear coefficient. A Brazilian sack of coffee traditionally weighs 60 kg.

The models were calibrated and tested for SSP and TRS, because we had 18 years of climatological data available for these locations. We used 1997-2007 data for calibration and 2008-2014 data for testing. The models for CRD, MSM, GXP, and SDS were only calibrated due to an insufficient amount of data (12 years). The average annual yields of coffee were provided by cooperatives and producers in the regions. The biennially development of coffee is due to the physiology of the plants, so the models were calibrated separately for years of high and low-yield to improve the accuracy.

Various methods are available for selecting the independent variables for multiple linear and nonlinear models, such as forward selection, backward elimination, stepwise, leaps and bounds regression, orthogonal descriptors, genetic algorithms, genetic populations, choosing operators, and fitness of evaluation. These methods seek to minimise the errors associated with the insertion or removal of variables in the models (Xu and Zang, 2001). These authors also stated that all possible combinations of the independent variables in the various equations for selecting the best model are possible when the number of independent variables is small.

Our study contained a large number of independent variables, but we tested all possible combinations (APC) of up to four independent variables in the models to avoid stability problems in local errors and for consistency in the analyses. The independent variables were the monthly DEFs during the phenological cycle of the crop, producing an average of 16 800 tested equations for each location. This total number of possible equations was due to the sum of all the possible equations

combining 1-4 independent variables. This total of possible combinations can be easily calculated using Newton's binomial equation (Mansour and Schork, 2011).

We removed models with multicollinearity between the independent variables (monthly DEFs). Multicollinearity is a problem in models analysing angular coefficients (weights), because it causes a bias in the coefficients (Gujarati and Porter, 2011). An analysis of the coefficients thus allowed us to infer which meteorological elements and at what time (month) these elements influenced the crop yield.

We verified the average reduction in coffee yield as a function of the annual DEF at the locations by analysing the elasticity of the coefficients as described by Gujarati and Porter (2011). We verified the influence of monthly DEF on yield during the coffee phenological cycle for the top 20 selected models with an analysis of correlations and the frequency of appearance of the variables.

The significance of the coefficients ($t < 0.05$) and the regression ($F < 0.05$), a low mean absolute percentage error (MAPE, %), and a high adjusted coefficient of determination (R^2_{adj}) were used for selecting the variables. The models were selected by an evaluation of the accuracy indicated by the MAPE and of the precision indicated by the R^2_{adj} (Cornell and Berger, 1987).

$$MAPE = \frac{\sum_{i=1}^n \left(\left| \frac{Y_{est_i} - Y_{obs_i}}{Y_{obs_i}} \right| \times 100 \right)}{n} \quad (4)$$

$$R^2_{adj} = \left[1 - \frac{(1-R^2) \times (n-1)}{n-k-1} \right] \quad (5)$$

where Y_{est_i} is an estimated variable, Y_{obs_i} is an observed variable, n is the number of datapoints (years), and, k is the number of independent variables in the regression. R^2 (unadjusted) was calculated by:

$$R^2 = \left(\frac{SQR + SQE}{SQR} \right) \quad (6)$$

where SQR is the regression sum of squares ($\sum (y_{est} - \bar{y}_{obs})^2$), and SQE is the sum of squared errors ($\sum (y_{obs} - y_{est})^2$).

Results and Discussion

Various authors have sought to understand the bienniality of coffee. The bienniality is an annual alternation of high and low-yield seasons, commonly

attributed to the restriction of photoassimilates produced by the plants. The photoassimilates in one year are allocated to the growth of branches, with little generation of productive germplasm. The photoassimilates of the next year are allocated to the germplasm, with little growth of the branches, generating a higher yield (Rodrigues et al., 2013b; Silva et al., 2008). Biennial production was generally higher in the SO_{MG} than the CE_{MG} locations. Bienniality averaged 14.8 sacks ha⁻¹ in SO_{MG} and 6.4 sacks ha⁻¹ in CE_{MG}. Bienniality was highest in SDS and MSM and lowest in TRS and CRD. The highest and lowest yields averaged 45.7 ±19.6 and 34.1 ±13.4 sacks ha⁻¹ in SDS and SSP, respectively (Fig 3).

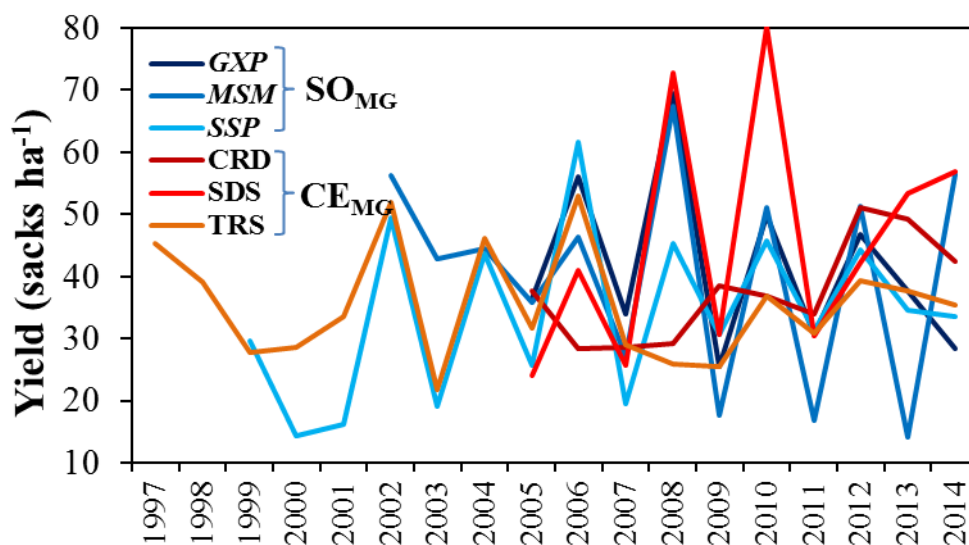


Fig 3. Yields of coffee in the South of Minas Gerais (SO_{MG}): GXP is Guaxupé, MSM is Monte Santo de Minas and SSP is São Sebastião do Paraíso, and in the Cerrado Mineiro (CE_{MG}): CRD is Coromandel, SDS is Serra do Salitre and, TRS is Tiros, State of Minas Gerais, Brazil.

The physiological cause of bienniality in coffee is complex but has been studied (Valadares et al., 2013; Melke and Fetene, 2014). When the coffee develops plagiotropic branches, photoassimilates are allocated to this growth, promoting a large vegetative flux in the plant. This growth simultaneously promotes the multiplication of the number of buds that would mature for production only in the following year (Pereira et al., 2011). The first year will thus have high vegetative growth and a low-yield. The following year will produce a high-yield due to the high bud formation in the previous year, but with low vegetative growth (Melke and

Fetene, 2014).

The photoassimilates in years with high-yields are allocated to bean filling, so vegetative growth is reduced, providing a lower yield again in the following year (Rodrigues et al., 2013b). Mature plagiotropic branches “self-prune”, reducing the useful area for production (Camargo and Camargo, 2001). This mechanism tends to reduce the bienniality of mature branches. The maturity of plagiotropic branches is reached in three or four years in these regions. Entire plants will reach this phase in six years.

A schematic synthesising the available information for the bienniality of coffee cultivation is presented in Fig 4. In addition to the strong physiological component, the weather directly influences the viability and quantity of the vegetative growth and the germplasm that will become the beans (Craparo et al., 2015).

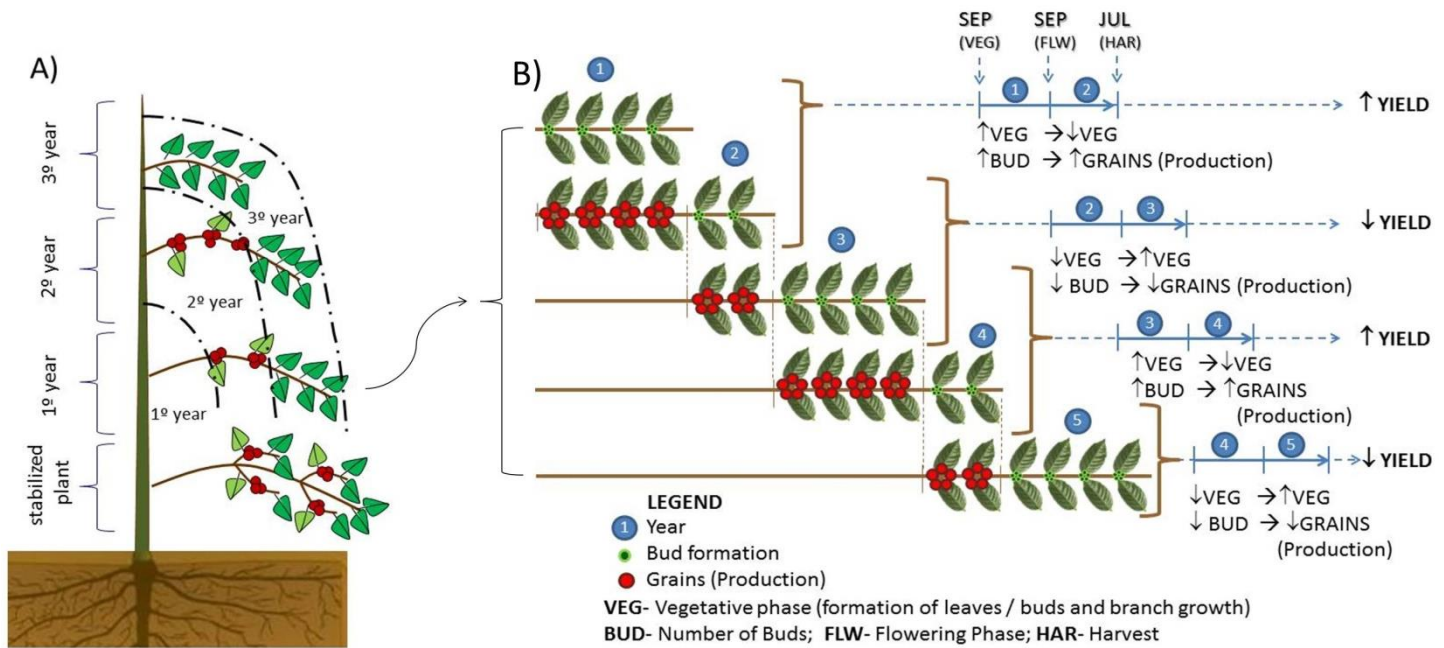


Fig 4. Coffee phenology A) plant development; B) plagiotropic branch development of coffee crop.

The DEFs were more intense in CE_{MG} , ranging from 269 to 613 mm cycle⁻¹. The cycle DEFs in SO_{MG} varied from 108 to 466 mm cycle⁻¹. The yields were more sensitive to DEF in CE_{MG} than in SO_{MG} . The average sensitivities as functions of DEF in SO_{MG} and CE_{MG} were -0.010 and - 0.031 $\frac{sacks\ ha^{-1}}{mm\ of\ DEF\ cycle^{-1}}$, respectively (Fig 5). A

sensitivity of $-0.031 \frac{\text{sacks ha}^{-1}}{\text{mm of DEF cycle}^{-1}}$ in coffee with an average yield of 45.00 sacks ha^{-1} represents a reduction of 3.10 sacks ha^{-1} for every 100 mm of cycle DEF. Assuming a DEF of zero during the cycle, an average yield in CE_{MG} would be 51.24 sacks ha^{-1} , which is 20% higher than in SO_{MG} (Fig 5.B). These values are similar to those reported by Fernandes et al. (2012) who found that the yield of coffee was usually higher in CE_{MG} than in SO_{MG} .

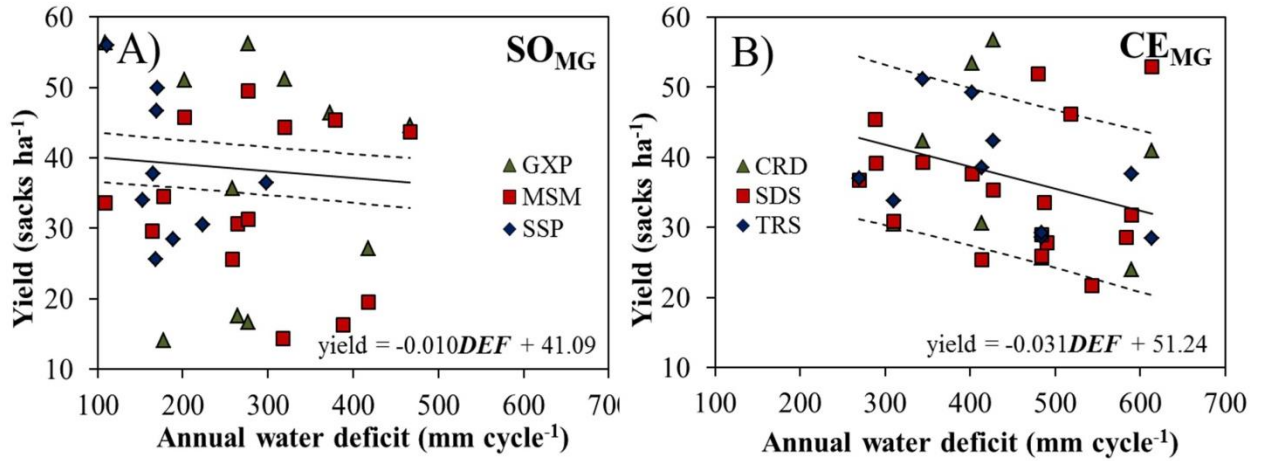


Fig 5. Relation of cycle water deficit and coffee yield in two main important coffee production in Brazil. A) South of Minas Gerais (SO_{MG}): GXP is Guaxupé, MSM is Monte Santo de Minas and, SSP is São Sebastião do Paraíso and, B) Cerrado Mineiro (CE_{MG}): CRD is Coromandel, SDS is Serra do Salitre and, TRS is Tiros. The linear regression has a confidence interval of 95%.

The stage of variable selection in the models for forecasting coffee yield by applying the APC method attempted to remove the equations with collinear variables. We tested a total of 16 830 equations for each location analysed and removed an average of 12 950 equations with collinear variables, leaving only 3 880 viable equations (Fig 6). These viable equations were assessed for a low MAPE, a high R^2_{adj} , and $p < 0.05$ (Fig 7).

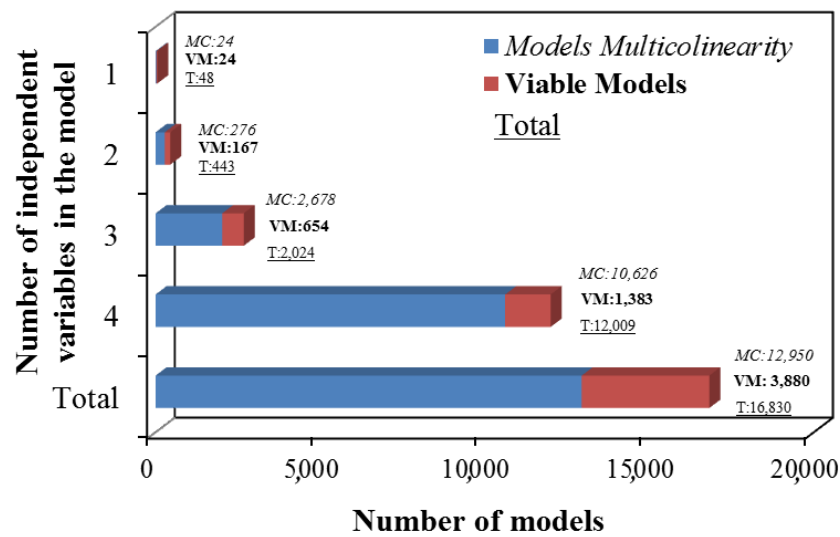


Fig 6. Total number of generated models, models with multicollinearity, and viable models for one region. Legend = VM is viable models, MC is models with multicollinearity and, T is Total number of models

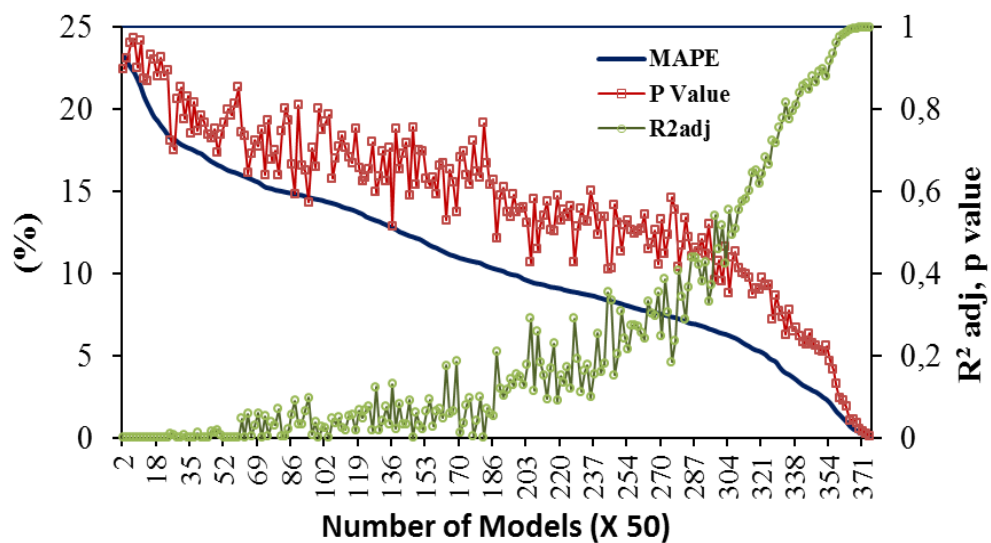


Fig 7. Model classification according to criteria the accuracy (lowest MAPE), precision (greater R^2 adj) and reliability (p - value).

To synthesise the information of the effect of DEFs on coffee yield, we identified the monthly DEFs of higher frequency in the yield forecasts of the 20 top designs for each location (Fig 8.A and B). A monthly DEF can be positively or negatively correlated with yield, depending on the phenological stage of the coffee (Syvertsen and Garcia-Sanchez, 2014).

DEFs in years of high-yield (Fig 8.A) had more influence on flowering, bean formation, and yield during the phenological year (y). The monthly DEF mostly influenced the phases of vegetative development and final maturation in years of low-yield (Fig 8.B). This result was in accordance with that by Pereira et al. (2011) who asserted that the growth of reproductive branches was the priority of development of the coffee in years with low-yields.

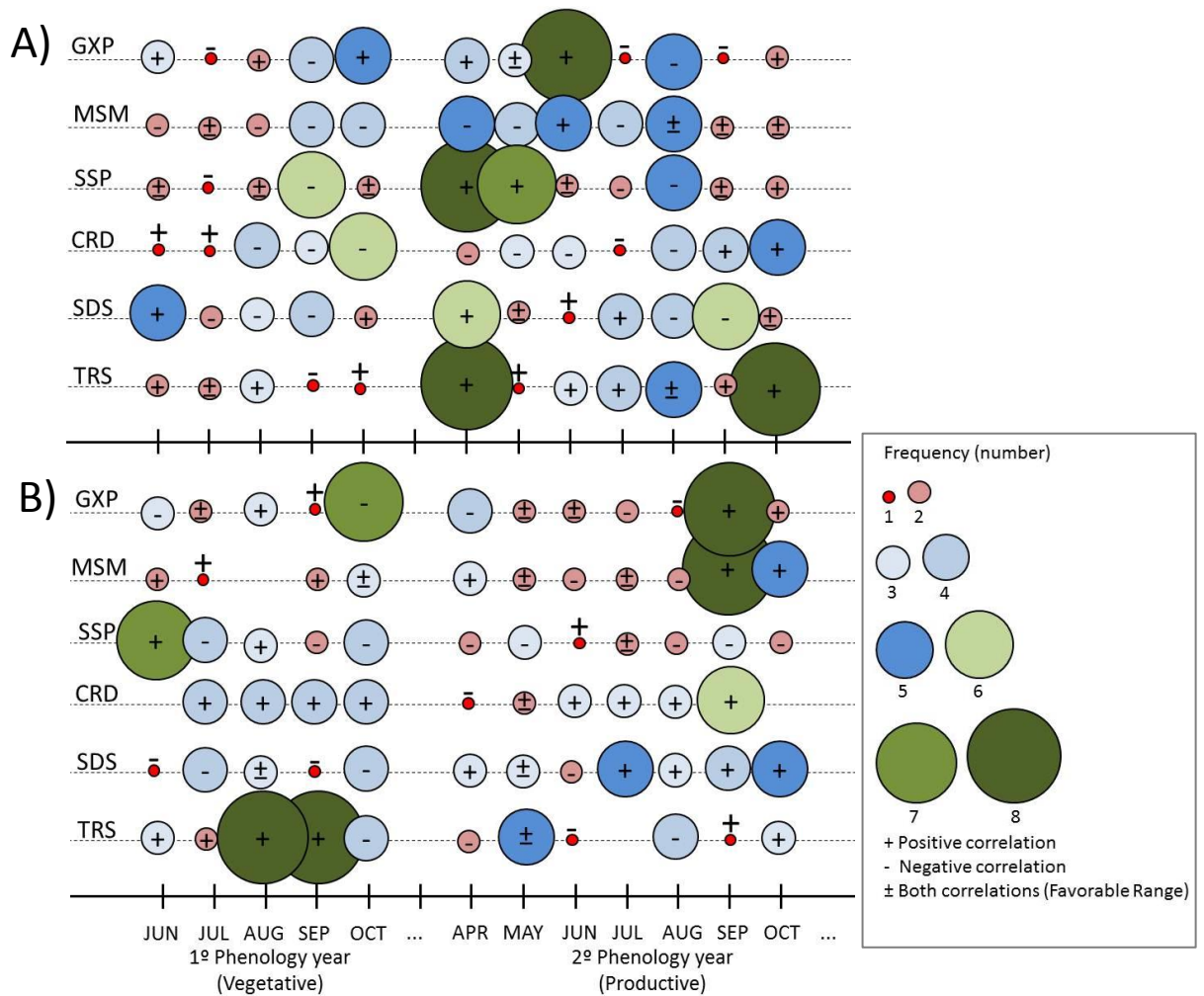


Fig 8. Frequency and correlation of the monthly water deficiency (DEF) with coffee yield of the selected 20 best models, high (A) and low-yield (B) seasons in the region of South of Minas Gerais (SO_{MG}): GXP is Guaxupé, MSM is Monte Santo de Minas, and SSP is São Sebastião do Paraíso and B) Cerrado Mineiro (CE_{MG}): CRD is Coromandel, SDS is Serra do Salitre, and TRS is Tiros, State of Minas Gerais, Brazil.

DEFs in years of high-yield had more influence during the production year (y), with higher frequencies in the models from April to July. The DEF in April of the second chronological year ($DEF_{APR(i-1)}$) in high-yield season was the most influential DEF (Fig 8.A). $DEF_{JUL(i-1)}$ occurred at the end in the growing period and had a smaller influence on coffee yield. CRD had an elevated level of soil-water storage in years of low-yields, so DEF had a small influence of the coffee.

$DEF_{SEP(i-1)}$ and $DEF_{OCT(i-1)}$ showed great influence both in high-yield as in low-yield season. $DEF_{SEP(i-1)}$ was very influential in the cultivation, negatively affecting the coffee high-yield (Fig 8.A). This stage is at the end of the dormancy when water restriction is desirable (Amarasinghe et al., 2015), together with strong and uniform flowering (Ronchi et al., 2015). $DEF_{OCT(i-1)}$, month of flowering, was negatively correlated with yield in GXP, SSP, SDS, and TRS (Fig 8), demonstrating that DEF in the flowering period of the coffee is not desirable.

The agrometeorological models were developed for associating coffee yield with monthly DEFs. The models were calibrated and tested for years with high-yields (Fig 9) and low-yields seasons (Fig 10) for understanding the limiting factors and incorporating the bienniality of coffee production. The adjusted angular coefficients indicated the sensitivity of yield in relation to the monthly DEF during the two years of the phenological cycle for each location.

The models developed for the years with high-yields were accurate, with a minimum MAPE of 0.39% (calibration) and an average forecasting period of up to nine months. For example, the model for forecasting the crop yield in MSM (Equation 7) had a forecasting period of six months, and the calibration was highly accurate, with a MAPE of 1.59% and an R^2_{adj} of 0.95. The MAPE of 1.59% in this model was considered low, because the average yield of 53.31 sacks ha^{-1} varied by ± 0.847 sacks ha^{-1} . October of the second phenological year ($i-1$) was the last month used in the model (equation 7), and the forecasting period for yield was six months, with harvesting beginning in May_(i) (Fig 2).

$$MSM_{High} = 4.55 \times DEF_{MAY(i-1)} + 0.779 \times DEF_{JUN(i-1)} - 1.479 \times DEF_{JUL(i-1)} - 0.585 \times DEF_{OCT(i-1)} + 59.14 \quad (7)$$

where $i-2$ is first chronological year, $i-1$ is the second chronological year, and i is the third chronological year.

Biennially:				High yields season						
Phenology				South of Minas Gerais			Cerrado Mineiro			
				GXP	MSM	SSP	CRD	SDS	TRS	
				DEF angular coefficients						
1° Phenological year (Vegetative) (y-1)	JUN	(i - 2)	Root system development Vegetative Growth BF BG	-0.428					0.199	
	JUL							-1.11		
	AUG									
	SEP			-0.48			0.071		-0.02	
	OCT						0.035			
	NOV									
	DEC									
	JAN	(i - 1)								
	FEB									
	MAR									
	APR			3.4		1.02		1.13	0.427	
	MAY				4.55	2.58	0.065		-0.24	
JUN				0.779	0.073					
2° Phenological year (Productive) (y)	JUL	(i - 1)		Dormancy FL PH GE GF MT HR	-1.47				-1.03	
	AUG									
	SEP							0.322		
	OCT				-0.585					
	NOV									
	DEC									
	JAN	(i)								
	FEB									
	MAR									
	APR									
	MAY									
	JUN									
JUL										
Linear coefficient					63.23	59.14	31.08	19.95	133.88	39.35
p - value regression					0.05	0.03	0.02	0.05	0.02	0.05
Average yield (sacks ha ⁻¹)					51.9	53.31	46.1	41.9	61.1	45.15
Calibration	MAPE (%)				1.01	1.59	1.81	0.41	0.39	2.94
	R ² Adj				0.98	0.95	0.96	0.99	0.99	0.7
Test	MAPE (%)			-	-	2.34	-	-	2.61	
	R ² Adj			-	-	0.86	-	-	0.72	
Monthly Anticipation				12	6	10	7	9	11	

Fig 9. Agrometeorological models using monthly water deficiency for forecast high-yield seasons of coffee arabica in the region of South of Minas Gerais (SO_{MG}): GXP is Guaxupé, MSM is Monte Santo de Minas, and SSP is São Sebastião do Paraíso and, Cerrado Mineiro (CE_{MG}): CRD is Coromandel, SDS is Serra do Salitre and, TRS is Tiros. Legend = BF is bud formation, BG is bud growth, FL is flowering, PH is pinhead, GE is grain expansion, GF is grain formation, and MT is maturation.

An analysis of the angular coefficients in this model identified $DEF_{MAY(i-1)}$ as the most important month and $DEF_{OCT(i-1)}$ as the least important month (Equation 7). $DEF_{JUL(i-1)}$ and $DEF_{OCT(i-1)}$ were negatively correlated with yield, probably because they were at the end of bud growth and flowering, respectively, when water restriction is usually not desirable. DEF during the vegetative period (bud growth) of a high-yield season in SO_{MG} was positively correlated with coffee yield. DEF_{JUL} at SDS in CE_{MG} in the vegetative and reproductive periods caused a reduction in the final yield (Fig 9).

The agrometeorological models developed for the years of low-yield were accurate, with a minimum MAPE of 0.14% and an average forecasting period of up to seven months. For example, the model for predicting the yield in GXP for a low-yield season (Equation 8) used $DEF_{OCT(i-1)}$ as the last month, so the forecasting period for yield forecasting was six months. The calibration was highly accurate, with a MAPE of 0.17% and an R^2_{adj} of 0.99. The MAPE of 0.17% in this model was considered low, because the average yield of 32.11 sacks ha^{-1} varied by ± 0.05 sacks ha^{-1} .

$$GXP_{Low} = -0.503 \times DEF_{OCT(i-2)} - 0.384 \times DEF_{APR(i-1)} + 0.106 \times DEF_{SEP(i-1)} + 0.014 \times DEF_{OCT(i-1)} + 34.5 \quad (8)$$

$DEF_{APR(i-1)}$, which occurs during bud growth, generally had a large influence on coffee yield in low-yield seasons. $DEF_{SEP(i-1)}$, at the end of dormancy, was positively correlated with coffee yield at GXP and MSM in SO_{MG} . DEF in June of the first chronological year ($DEF_{JUN(i-2)}$) had a positive influence on yield at SSP. The coffee prepares to begin vegetative growth during this period, and the roots grow intensively, which is favoured by DEF (Larcher, 2004).

$DEF_{OCT(i-2)}$ caused a reduction in the final yield at CRD and SDS in CE_{MG} . $DEF_{APR(i-1)}$ had a negative influence on coffee yield at CRD and TRS, because the buds normally grow in this month, a time when the coffee crop needs evapotranspiration to form the reproductive buds. DEFs during dormancy $_{(i-1)}$ had a positive influence on yield at SDS (Fig 10). Ronchi et al. (2015) suggested that DEFs were desirable in August $_{(i-1)}$, which favours uniformity and the yield of the coffee crop.

Biennially:				Low yields season						
Phenology				South of Minas Gerais			Cerrado Mineiro			
				GXP	MSM	SSP	CRD	SDS	TRS	
				DEF angular coefficients						
1° Phenological year (Vegetative) (y-1)	JUN	(i - 2)	Root system development Vegetative Growth BF BG			0.281				
	JUL									
	AUG									
	SEP					-0.187			0.008	
	OCT			-0.503			-0.049	-0.08		
	NOV									
	JAN	(i - 1)								
	FEB									
	MAR									
	APR			-0.384	0.294	-0.526	-0.365		-0.154	
	MAY									
	JUN									
2° Phenological year (Productive) (y)	JUL	(i - 1)		Dormancy FL PH GE GF MT HR					0.596	
	AUG					-0.08		-0.174	0.347	
	SEP				0.106	0.38				0.023
	OCT				0.014			0.100	0.127	
	NOV									
	DEC									
	JAN	(i)								
	FEB									
	MAR									
	APR									
	MAY									
	JUN									
JUL										
Linear coefficient					34.52	9.6	31.65	43.85	-11.86	29.24
p - value regression					0.02	0.02	0.04	0.04	0.01	0.05
Average yield (sacks ha ⁻¹)					32.11	22.23	23.4	32.5	32.3	28.02
Calibration	MAPE (%)				0.17	0.79	3.41	0.33	0.14	2.9
	R ² Adj				0.99	0.99	0.93	0.99	0.99	0.70
Test	MAPE (%)			-	-	2.43	-	-	9.4	
	R ² Adj			-	-	0.86	-	-	0.90	
Monthly Anticipation				6	7	12	6	6	7	

Fig 10. Agrometeorological models using monthly water deficiency for forecast low-yield seasons of coffee arabica in the region of South of Minas Gerais (SO_{MG}): GXP is Guaxupé, MSM is Monte Santo de Minas, and SSP is São Sebastião do Paraíso and, Cerrado Mineiro (CE_{MG}): CRD is Coromandel, SDS is Serra do Salitre and, TRS is Tiros. Legend = BF is bud formation, BG is bud growth, FL is flowering, PH is pinhead, GE is grain expansion, GF is grain formation, and MT is maturation.

Conclusions

The testing of all possible combinations of variables for the selection of monthly water deficits and the use of multiple linear regressions for forecasting coffee yield for two regions in Minas Gerais, Brazil, were efficient.

The agrometeorological models developed as functions of water deficits were accurate for all regions, and the minimum forecasting period for yield was six months for the region of the South of Minas Gerais and Cerrado Mineiro.

The coffee in years of high-yield was influenced more by water deficit in the reproductive phase, corresponding to the second phenological year. Water deficits in years with low-yields had a larger influence in the vegetative phase of the crop, corresponding to the first phenological year.

Acknowledgements

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CAPÍTULO 3 – Agrometeorological models for forecasting *Coffea arabica* yield

ABSTRACT - Many forecasting techniques have been tested with crop models using various statistical analyses for generating future scenarios of yield. Forecasting, however, can be achieved by simply using regression analysis and carefully selecting independent variables (IVs) with time displacement relative to the dependent variable. The early forecasting of yield is the vanguard of agronomic modelling, promoting improvements in planning, allowing more rational strategic decisions, and increasing food and economic security. Climatic parameters are the most important factors controlling yields and the quality of coffee in areas of plantations. We calibrated and tested agrometeorological models to forecast the annual yield of *Coffea arabica* for six traditional producing regions in the state of Minas Gerais, Brazil. We used multiple linear regressions, selecting IVs to maximise the period between the forecast of yield and the harvest for each locality. The IVs were monthly meteorological parameters from 1997 to 2014: air temperature, rainfall, potential evapotranspiration, soil water storage, water deficit, and the water surplus. The IVs were selected by testing all possible IV combinations, avoiding multicollinearity. The better models minimised the mean absolute percentage error and had a coefficient of determination (adjusted R^2) near 1, and only models with significance level of 0.01 were selected. The agrometeorological models were accurate for all regions, and the earliest forecasts were six and five months before harvest for the producing locations of Guaxupé and Coromandel, respectively. The coffee yield was controlled by all meteorological parameters in southern Minas Gerais and by hydric parameters (rainfall and water deficiency and surplus) in the Cerrado Mineiro region in northwestern Minas Gerais.

Key Words: water deficit, prediction, crop model, yield forecast, early prevision.

Introduction

Brazil has the world's largest production of coffee (*Coffea arabica* L.)

(Amarasinghe et al., 2015), but few studies have addressed the forecasting of yield as a function of meteorological parameters (Rodrigues et al., 2013). Coffee in Brazil is grown in unshaded areas, different from the conditions in Ethiopia, coffee's native country, where the coffee is grown under semi-forest shaded conditions (Gomes et al., 2008; Aerts et al., 2011). Meteorological parameters have the most influence on agricultural production (Craparo et al., 2015, Brixner et al., 2014).

Climatic variability has a strong impact on agricultural activities (Sá Junior et al., 2012). Air temperature, solar radiation, and rainfall are the most critical meteorological parameters in agricultural production (Hoogenboom, 2000). Camargo (2010) reported that the variation in air temperature and the distribution of rainfall had the most effect on phenology and yield in coffee cultivation.

Solar radiation provides the energy for photosynthesis necessary for crop yields (Oliveira et al., 2012, Angelocci et al., 2008). The air temperature regulates the rates of vegetative and reproductive growth, but higher air temperatures can cause flowers to abort (Pereira et al., 2008). Damatta and Ramalho (2006) reported that continuous exposure to temperatures above 30 °C reduced growth and even caused foliar yellowing, commonly known as scald.

Water deficit is one of the main factors reducing the yield of crops (Khamssi et al., 2011; Sakai et al., 2015), because it reduces the rate of evapotranspiration, the uptake of water by the roots, the distribution of the root system, and the canopy size (Amarasinghe et al., 2015). Water stress is responsible for decreases in coffee production (Carvalho et al., 2011), especially when water stress occurs after fertilisation and graining, thus damaging the filling of fruits (Camargo, 2010).

Agrometeorological modelling can efficiently quantify these climatic effects on crop yields (Rolim et al., 2008). These models correlate climatic parameters with plant physiology (Jones; Kiniry, 1986) and can estimate (Jame; Cutforth, 1996) or forecast (Gouranga; Ashwani, 2014) yield. Agrometeorological models are tools for planning activities in enterprises and cooperatives and can identify the most influential meteorological variables in the phenological phases.

The quantification of a future event using currently available data is known as forecasting, different from estimation that quantifies a current phenomenon using current data (Rolim et al., 2008). Few models can forecast crop yield. Mkhabela,

Mkhabela and Mashinini (2005) forecast corn crops two months in advance of the harvest in Swaziland using data from the Normalized Difference Vegetation Index (NDVI) derived from the NOAA-Advanced Very High Resolution Radiometer. Mkhabela et al. (2011) used NDVI data of the resolution imaging spectroradiometer of MODIS to accurately forecast barley, pea, and wheat yields on the Canadian prairies two months in advance. Gouranga and Ashwani (2014) predicted rice yield 30 days in advance of the harvest in India. Marcari et al. (2015) used agrometeorological models to predict sugar cane productivity near Jaboticabal, Brazil, five months before the harvest.

Model applicability can be improved to obtain advanced forecasts of crop yields by using both meteorological and climatic data in global circulation models (GCMs). Hansen et al. (2004) accurately forecasted wheat yield in northeastern Australia before planting using patterns of El Niño and La Niña, and Kogan et al. (2013) forecasted wheat productivity in the Ukraine two to three months in advance using NDVI data associated with GCMs used for meteorological forecasting.

The quantification of the influence of climatic parameters on phenology and yield in coffee plantations is complex. We thus calibrated and tested agrometeorological models to predict the annual yield of *C. arabica* in the producing regions of the Brazilian state of Minas Gerais and to identify the most important monthly meteorological parameters for coffee yield.

Materials and Methods

We used historical series of climatic and phytotechnical data from Guaxupé (GXP), Monte Santo de Minas (MSM), and São Sebastião do Paraíso (SSP) in southern Minas Gerais (SO_{MG}) and for Coromandel (CRD), Serra do Salitre (SDS), and Tiros (TRS) in Cerrado Mineiro (CE_{MG}). The CE_{MG} locations were irrigated (Table 1 and Figure 1).

Table 1. Geographic and Climatic characteristics of the regions used.

Regions	South of Minas Gerais			Cerrado Mineiro		
	GXP	MSM	SSP	CRD	SDS	TRS
Altitude (m)	824	892	973	928	1244	977
Latitude (S)	21°18'13"	21°11'44"	20°54'36"	18°28'19"	19°05'50"	18°59'53"
Longitude (W)	46°42'31"	46°57'46"	47°06'34"	47°11'34"	46°40'25"	45°58'11"
Climate ¹	B ₂ rB' ₄ a'	B ₃ rB' ₃ a'	B ₄ rB' ₂ a	B ₂ wB' ₃ a'	B ₂ wB' ₃ a'	B ₂ wB' ₃ a'
C/T ²	C	C	C/T	C	C	C/T

¹Classification Climatic of Thornthwaite (1948); ²C is calibration and T is test;



Fig 1. Regions utilized in the study in the State of Minas Gerais, Brazil. Guaxupé (GXP), Monte Santo de Minas (MSM), São Sebastião do Paraíso (SSP), Coromandel (CRD), Serra do Salitre (SDS), and Tiros (TRS).

Climatic data for the regions from 1997 to 2014 were collected daily by automated meteorological stations. The climatic parameters used were rainfall (P) and air temperature (T). Daily T and P data were transformed to a monthly scale for calculating evapotranspiration (PET) using the model proposed by Camargo and Camargo (2000) (Eq. 1), which is similar to the calculations by Thornthwaite (1948) for tropical regions, with the advantage of not having the normal monthly temperatures of the localities (Camargo; Camargo, 2000). The calculations were performed on a monthly scale to represent the phenological phases of the coffee crop (Figure 2).

$$PET = 0.01 \times Q_o \times T \times ND \quad (1)$$

where Q_o is daily solar atmospheric irradiance (mm day^{-1}); T is mean air temperature ($^{\circ}\text{C}$), and ND is number of days.

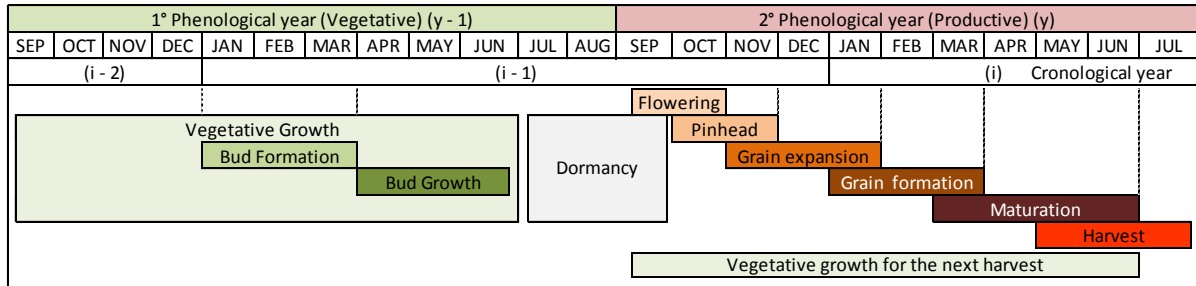


Fig 2. Phenology of the *Coffee Arabica* L. (modified from Camargo and Camargo, 2001). Indexes = $y-1$ is first phenological year, y is second phenological year, $i-2$ is first chronological year, $i-1$ is second chronological year and i is third chronological year.

Monthly soil water storage (STO), actual evapotranspiration (AET), water deficiency (DEF), and water surplus (SUR) were calculated as described by Thornthwaite and Mather (1955) (Eqs. 2-7), with an available water-storage capacity of 100 mm.

$$\text{if } (P - PET)_i < 0 = \begin{cases} NAC_i = NAC_{i-1} + (P + PET)_i \\ STO_i = WC e^{\frac{(NAC_i)}{WC}} \end{cases} \quad (2)$$

$$\text{if } (P - PET)_i \geq 0 = \begin{cases} STO_i = (P - PET)_i + STO_{i-1} \\ NAC_i = WC \ln \frac{(STO_i)}{WC} \end{cases} \quad (3)$$

$$ALT_i = STO_i - STO_{i-1} \quad (4)$$

$$AET_i = \begin{cases} P + |ALT_i| & , \text{if } ALT < 0 \\ PET_i & , \text{if } ALT \geq 0 \end{cases} \quad (5)$$

$$DEF = PET - AET \quad (6)$$

$$SUR_i = \begin{cases} 0 & , \text{if } WC < 0 \\ (P - PET)_i - ALT_i & , \text{if } WC = 0 \end{cases} \quad (7)$$

where PET is potential evapotranspiration (mm); WC is available water capacity (mm); STO is soil water storage (mm); NAC = Sum rainfall – potential evapotranspiration; P is rainfall (mm); DEF is water deficiency at the soil-plant-atmosphere system (mm); AET is actual evapotranspiration (mm); SUR is water surplus at the soil-plant-atmosphere system (mm); ALT is soil water storage of the

current month – soil water storage of the preceding month (mm) and, i is the monthly period.

The analysis included two steps. First, we determined the relationships between annual coffee yield and annual meteorological parameters (T, P, PET, SUR, and DEF) to clarify the limits and general tendencies of the relationships. Second, we analysed the ratios of annual yield to the monthly meteorological parameters to understand their relationships with coffee phenology and to develop agrometeorological models for forecasting crop yield. We used multivariate principal component analysis (PCA) in this step for all regions combined and the generation of agrometeorological models.

Forecasting coffee yields used models of multiple linear regressions (Eq. 8). The monthly meteorological parameters corresponding to the two years of the phenological cycle of coffee were the independent variables. Multiplying the six variables for 23 months of coffee phenology gave a total of 138 independent variables (X) tested for each location:

$$Yield = \alpha \times X_1 + \beta \times X_2 + \gamma \times X_3 + \dots + \omega \quad (8)$$

where $X_1, X_2, X_3, \dots$ are the selected monthly meteorological parameters; $\alpha, \beta, \gamma, \dots$ are the adjusted coefficients (weight); and ω is the linear coefficient. A Brazilian sack of coffee traditionally weighs 60 kg.

We restricted the number of independent variables in the model to three or fewer; that is, we tested all possible models with one, two, or three independent variables for each locality. The total number of possible models can be calculated by Newton's binomial $\left(\binom{n}{p} = \frac{n!}{p!(n-p)!} \right) = 138 + 9453 + 428\,536$, totalling 438 127 models for each locality. Independent variables with no variation were previously removed from the analysis, e.g. STO in humid periods.

A correlation matrix was constructed to verify the multicollinear independent variables. The variables with a correlation of $r \geq |0.7|$ were removed from the analyses, which permitted the evaluation of the angular coefficients of the models and allowed the evaluation of the most influential variables in forecasting (Gujarati;

Porter, 2011; Gouranga; Ashwani, 2014).

The selection of the independent variables to be combined to generate significant models is a major drawback of multiple linear regression (Walpole et al., 2011). We tested all possible combinations (APC) up to three independent variables for each model, even with the large number of independent variables (138), and analysed the entire system of the domain set. The models were selected based on the significance of the coefficients ($t < 0.05$) and the regressions ($F < 0.05$) for maximising the adjusted R^2 (R^2_{adj}) (Cornell; Berger, 1987) and minimising the mean absolute percentage error (MAPE, %) (Eqs. 9 and 10, respectively).

$$R^2_{adjusted} = \left[1 - \frac{(1-R^2) \times (n-1)}{n-k-1} \right] \quad (9)$$

$$MAPE = \frac{\sum_{i=1}^n \left(\left| \frac{Y_{est_i} - Y_{obs_i}}{Y_{obs_i}} \right| \times 100 \right)}{n} \quad (10)$$

where R^2 is determination coefficient (%), n is number of data (years), k is number of independent variables in the regression, Y_{EST_i} is estimated variable and, Y_{OBS_i} is observed variable.

The data for average annual coffee yield were provided by the cooperatives and producers in the regions. Coffee has a high biannuality between crops, deriving from the physiology of the plants (Pereira et al., 2011), so the developed models were calibrated separately for high- and low-yield seasons. The separate calibrations did not restrict the forecasting, because producers and agricultural businesses in the regions know the physiological condition of the plants for the next harvest (high or low).

The models developed for SSP and TRS were used for calibration and testing, because the climatic series had 18 years of data; 12 years were used to calibrate the models and 6 years were used for testing. The models developed for CRD, MSM, GXP, and SDS were only calibrated, because the climatic series contained only 12 years of data.

Results and Discussion

In the evaluation of the annual climatic parameters, the increase in average T

and the annual increase in SUR increased yield (Figure 3A, B, G, and H). The highest annual T used in the study was 23.5 °C, because higher temperatures can decrease yield and because the optimal temperature range for arabica coffee is between 18 and 23 °C (Assad et al., 2004). The increase in PET and DEF decreased annual average coffee yield (Figure 3E, F, I, and J), because high PETs during periods of low STO produce DEFs that decrease vegetative growth and yield (Sakai et al., 2015; Batista et al., 2010). Yield was maximised in the southern Minas Gerais and Cerrado regions when annual P was between 1400 and 1600 mm y⁻¹ (Figure 3C and D).

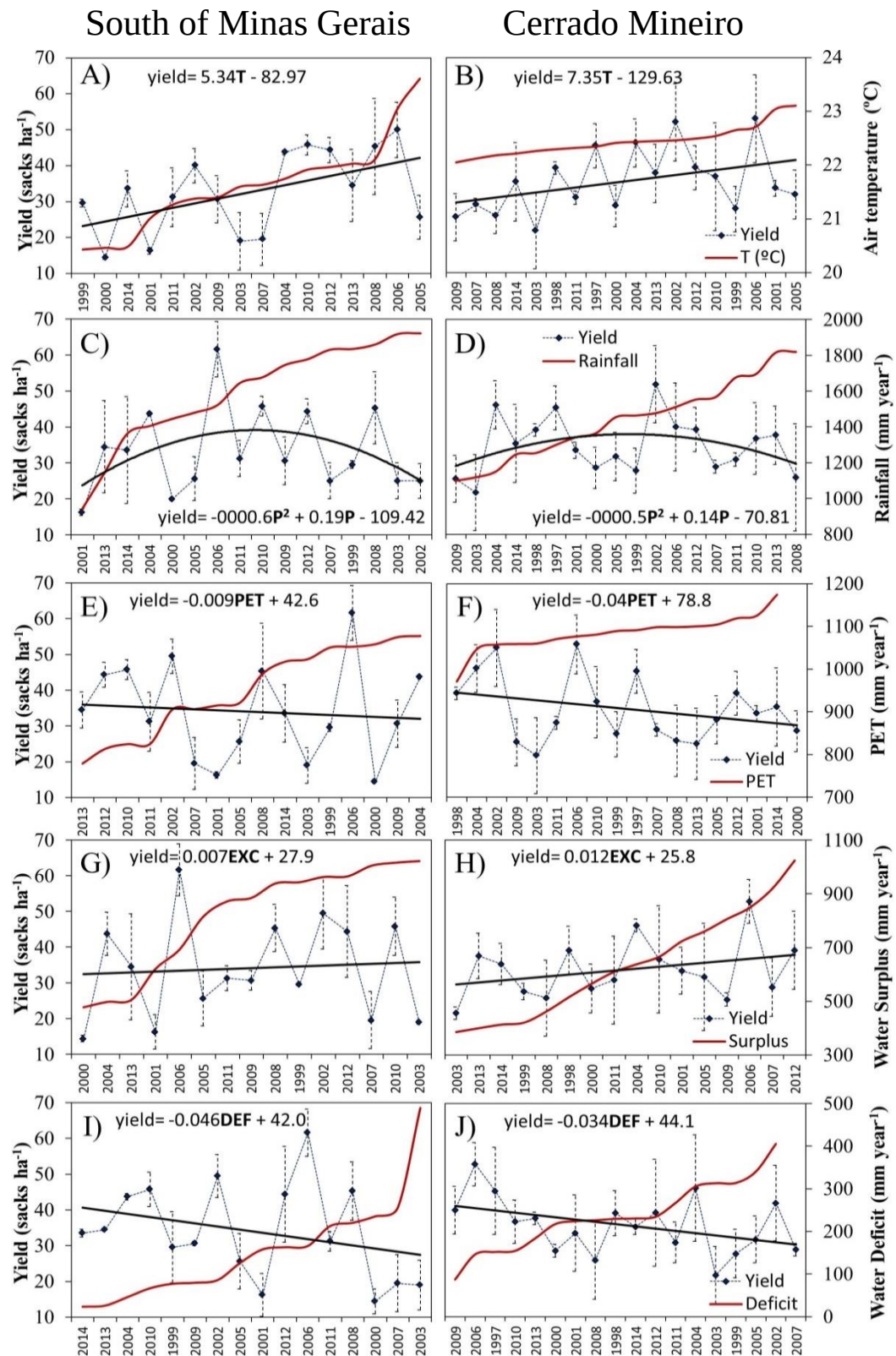


Fig 3. Yield of the *Coffea arabica* L. in function of the ordered annual meteorological elements in the South of Minas Gerais (A; C; E; G and I) and Cerrado Mineiro (B; D; F; H and J).

The multivariate PCA determined the influence of the general meteorological parameters on the yield of *C. arabica* based on plant phenology. Each southern Minas Gerais and Cerrado region was analysed separately, but the responses were very similar, so we have presented a joint analysis only (Figure 4). The yields of *C. arabica* in the southern Minas Gerais (SO_{MG}) and Cerrado Mineiro (CE_{MG}) regions were strongly dependent on the weather. The PCA analysis showed that the first two components (PC1) and (PC2) together accounted for 94.93% of the total variability of the data.

P, DEF, SUR, PET, and T had large impacts on coffee yield in the regions (Figure 4). SUR during vegetative growth (SUR_{VG}) and grain formation (SUR_{GF}), in addition to P during bud growth (P_{BG}) and fruit maturation (P_{MT}), were favourable and increased coffee yield. Even though P_{MT} is favourable to yield, its occurrence is not necessary (Abrahão et al., 2009), because it favours the proliferation of fungi, which decreases the natural quality of the coffee. DEF during the pinhead stage (DEF_{PI}) was also directly correlated with yield, confirming the benefit to the coffee of DEF at moderate intensities in some stages (Batista et al., 2010).

An increase in T during vegetative growth (T_{VG}) and an increase in potential evapotranspiration during flowering (PET_{FL}) and vegetative growth (PET_{VG}) were inversely proportional to coffee yield (Figure 4), likely because gas exchange decreases in the plants when subjected to high T and PET, thus decreasing photosynthesis (Taiz; Zauger, 2011).

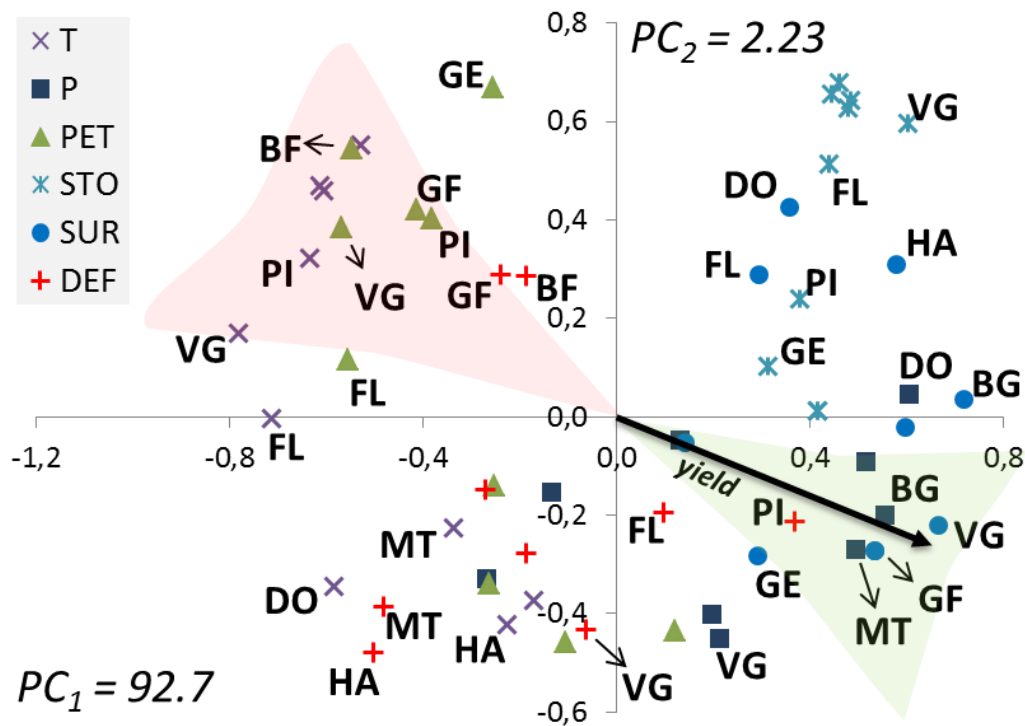


Fig 4. Biplot (main component, PCA) of the yield annual of *Coffea arabica* L. in function of phenology of the *Coffee Arabica* in the South of Minas Gerais and Cerrado Mineiro. Legend = T is air temperature (°C), P is rainfall (mm), PET is potential evapotranspiration (mm), STO is soil water storage (mm), DEF is water deficit (mm), SUR is water surplus (mm), VG is vegetative growth, BF is bud formation, BG is bud growth, DO is dormancy, FL is flowering, PI is pinhead, GE is grain expansion, GF is grain formation, MT is maturation and, HA is harvest.

CE_{MG} had a DEF between April and November, with intensities of 50 mm (August) and an annual accumulated DEF of 226.4 mm (Figure 5B), which explains why most of the coffee areas in the region have irrigation systems to provide water for cultivation, because an annual DEF above 150 mm requires an artificial water supply (Assad et al., 2004). DEF occurred in SO_{MG} from May to October, with a lower annual cumulative DEF of 94.36 mm (Figure 5A), which traditionally has not required the need for irrigation. SUR occurred in summer (November to March), at 672.9 mm in SO_{MG} and 586.7 mm in CE_{MG} (Figure 5B).

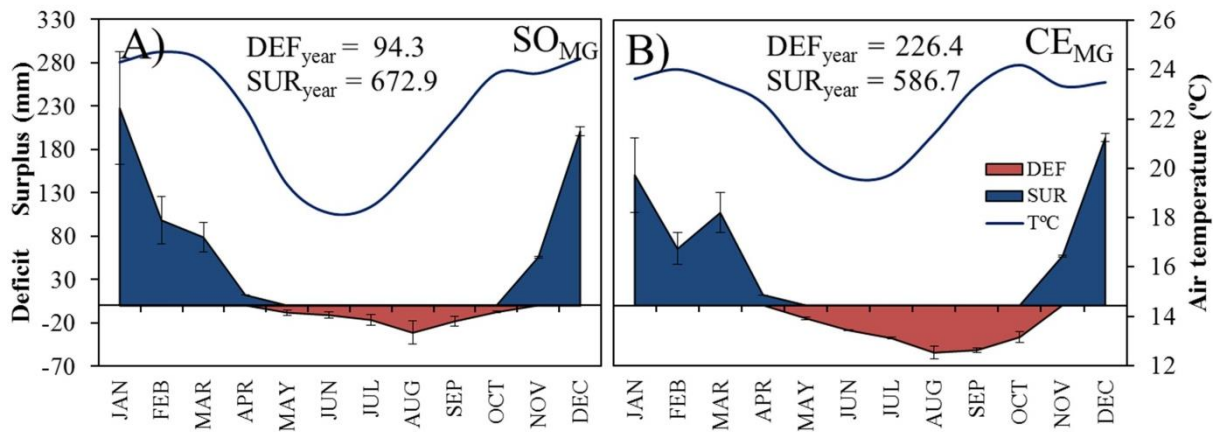


Fig 5. Air temperature and water balance for South of Minas Gerais (SO_{MG}) and Cerrado Mineiro (CE_{MG}). Legend: SUR is water surplus (mm month⁻¹), DEF is water deficit (mm month⁻¹) and, T is the monthly average air temperature (°C).

Selecting the independent variables for forecasting coffee yield by testing all possible combinations allowed us first to remove the equations with multicollinear variables. For example, a total of 37 246 equations were calibrated for Guaxupé, with up to three independent variables, but the removal of multicollinear variables decreased the number of viable models to 17 597 (Figure 6). These viable equations with the best designs were selected for their lower MAPE and p and higher R^2_{adj} (Figure 7).

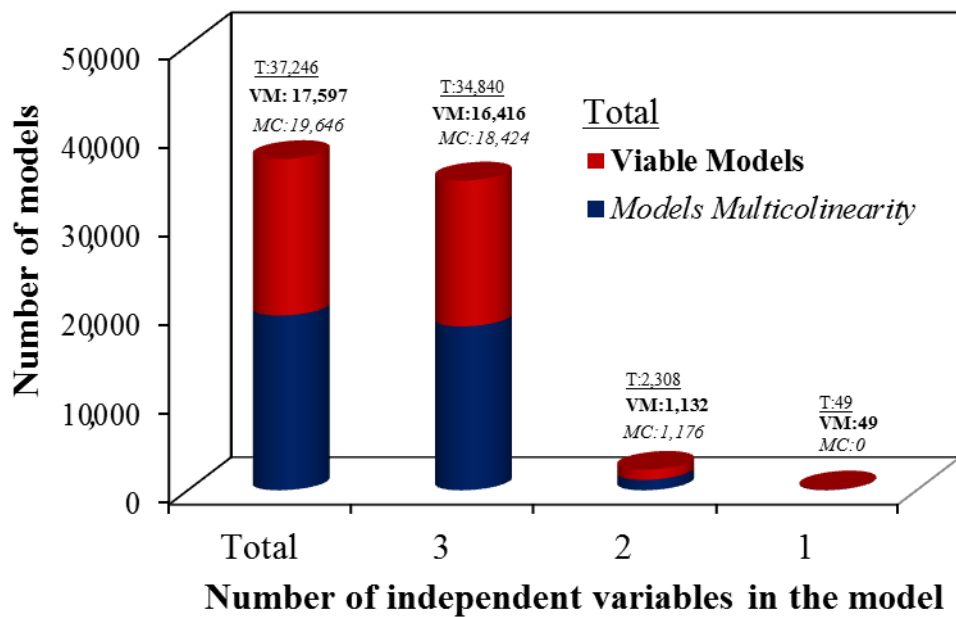


Fig 6. Total models calibrated to Guaxupé in high-yield seasons. VM = viable models (red), MC = models with multicollinearity (blue) and, T = Total number of models.

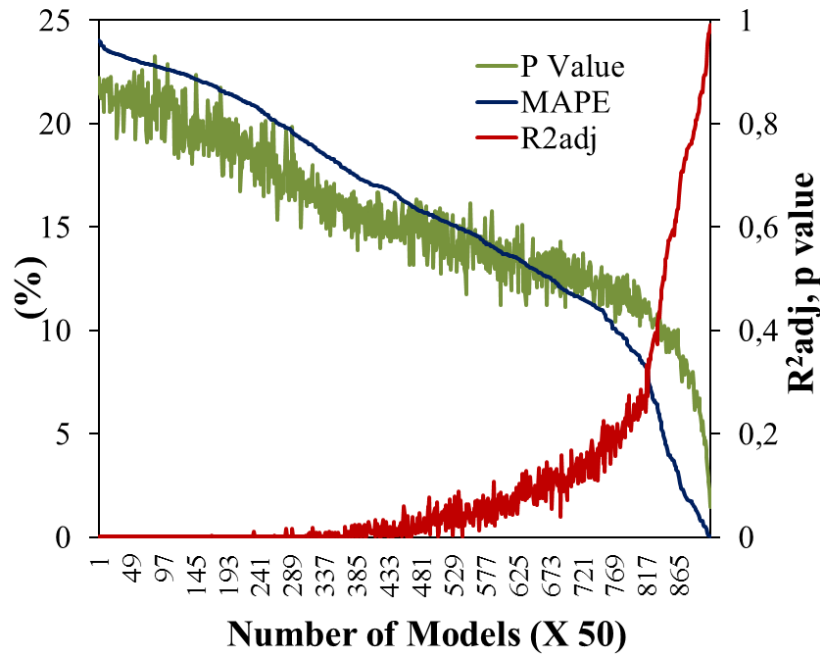


Fig 7. Example of classification of agro-meteorological models according to accuracy (MAPE), precision (R^2 adj) and reliability (p-value) criteria.

Coffee has a high biannuality between crops due to the physiology of the plants, so the developed models were calibrated separately for high- and low-yield years to improve the accuracy of the models. The calibrated models for forecasting *C. arabica* yield in the southern Minas Gerais region were all accurate (Table 2).

The models calibrated for GXP had a MAPE of 0.57% and an R^2 adj of 0.99 (Table 2, Eq. 1) for high-yield seasons and a MAPE of 0.90% and an R^2 adj of 0.99 (Eq. 4) for low-yield seasons. A MAPE of 0.90% is low, because an average yield of 36.6 sacks ha^{-1} varies by only ± 0.33 sacks ha^{-1} . To forecast a high-yield season in GXP, the DEF in October of the second chronological year ($\text{DEF}_{\text{OCT}(i-1)}$) was the last meteorological parameter used in the model. As the harvest begins in May of the productive year ($\text{May}_{(i)}$) the model can forecast six months before the harvest.

The period between the yield forecast and the harvest obtained by the models for MSN and SSP was 10 months for both, because the last elements required for the forecasts were $\text{TJUN}_{(i-1)}$ and $\text{DEFJUN}_{(i-1)}$, respectively (Table 2).

Table 2. Agrometeorological models in function of monthly meteorological elements for forecast high and low-yield of *Coffea arabica* L. in the region of South of Minas Gerais (SO_{MG}): GXP is Guaxupé, MSM is Monte Santo de Minas and, SSP is São Sebastião do Paraíso. The independent variables are, T is air temperature (°C), P is rainfall (mm), PET is potential evapotranspiration (mm), DEF is water deficit (mm), and SUR is water surplus (mm).

Agrometeorological models			p-value	Calibration		Test	
				MAPE (%)	R ² Adj	MAPE (%)	R ² Adj
High-yields season							
(1)	GXP	Y = - 0.151.DEFJUL _(i-1) - 0.579.DEFOCT _(i-1) + 0.473.PJUL _(i-1) + 36.6	0.001	0.57	0.99	-	-
(2)	MSM	Y= 0.585.PAUG _(i-2) - 0.239. PMAY _(i-2) + 0.175. POCT _(i-2) + 24.9	0.002	2.17	0.96	-	-
(3)	SSP	Y = 0.77.DEFJUN _(i-1) - 0.068.SURJAN _(i-1) + 0.38.DEFSEP _(i-2) - 35.65	0.004	3.13	0.91	4.65	0.91
Low-yields season							
(4)	GXP	Y = - 0.496.DEFAPR _(i-1) + 4.77.TSEP _(i-1) + 0.127.POCT _(i-1) - 82.10	0.002	0.90	0.99	-	-
(5)	MSM	Y= 0.704.PETAPR _(i-1) + 1.49. TJUN _(i-1) + 0.101. SURNOV _(i-2) - 70.42	0.002	1.01	0.99	-	-
(6)	SSP	Y = 0.183.DEFOCT _(i-2) + 0.017.SURDEC _(i-2) + 0.05.PFEB _(i-2) - 9.04	0.001	2.08	0.97	3.61	0.99

* $i-2$ is first chronological year and, $i-1$ is the second chronological year.

The results of variable selection by APC methodology had corresponded to plant phenology. The average yield for SO_{MG} was controlled by both hydric (DEF and P) and energetic (T and PET) parameters. DEF in GXP decreased yield; all angular coefficients were negative. DEFOCT_(i-1) during flowering was the most important variable in high-yield seasons, and increasing TSEP_(i-1) before flowering was most relevant in low-yield seasons.

DEFJUL_(i-1) and DEFOCT_(i-1) during production in high-yield seasons in GXP were inversely correlated with yield, because they affected the growth of the productive buds and flowers, respectively. The angular coefficient was higher for DEFOCT_(i-1) than DEFJUL_(i-1), indicating that the coffee was highly sensitive to DEF during flowering, the phase in which water stress is not desirable (Silva et al., 2009). A DEFOCT_(i-1) of 1 mm decreased yield by 0.579 sacks ha⁻¹ (Table 2).

DEF decreased yield because it reduces the evapotranspiration rate of the crop and consequently decreases photosynthesis (DaMatta, 2004). PJUL_(i-1) had a direct effect on yield, because it favours the end of the growth of buds and the start of dormancy (Figure 2). Rain at this stage, however, is not important, because it affects fruit maturation and consequently the quality of the coffee (Abrahão et al., 2009).

DEFAPR_(i-1) decreased yield in the low-yield season for GXP, because it affects the formation and growth of new production buds. A DEF_{OCT}_(i-1) of 1 mm decreased the average yield by 0.496 sacks ha⁻¹. Higher POCT_(i-1) and TSEP_(i-1) increased yield, because the supplies of energy and water to the plants were higher during flowering (Figure 2).

The models calibrated for the Cerrado Mineiro region accurately forecasted yield, the largest MAPEs were 2.82 and 5.95% during calibration and testing, respectively, for the models developed for high-yield seasons in TRS (Table 3). The models calibrated for CRD were the most accurate, with a MAPE of 0.09% and an R^2 adj of 0.99 in the high-yield seasons and a MAPE of 0.04% and an R^2 adj of 0.99 in the low-yield seasons.

The water surplus in November of the second chronological year (SURNOV_(i-1)) was the last meteorological parameter used in the model for CRD. The harvest begins in May_(i), providing a forecast period five months before the harvest. SDS and TRS provided forecasts 6 and 11 months before the harvest, respectively. The last meteorological parameters used in those cases were POCT_(i-1) and PMAY_(i-1) (Table 3), respectively.

Table 3. Agrometeorological models in function of monthly meteorological elements for forecast high and low-yield of *Coffea arabica* L. in the region of Cerrado Mineiro (CE_{MG}): CRD is Coromandel, SDS is Serra do Salitre and, TRS is Tiros. The independent variables are, T is air temperature (°C), P is rainfall (mm), PET is potential evapotranspiration (mm), DEF is water deficit (mm), and SUR is water surplus (mm).

Agrometeorological models		p-value	Calibration		Test	
			MAPE (%)	R ² Adj	MAPE (%)	R ² Adj
High-yields season						
(1) CRD	Y= - 0.034.SURNOV _(i-1) + 0.0067.PFEB _(i-1) - 0.332.PSEP _(i-1) + 55.47	0.001	0.09	0.99	-	-
(2) SDS	Y = - 0.815.DEFAUG _(i-1) + 4.22.PJUL _(i-1) + 0.135. POCT _(i-1) - 85.61	0.001	0.26	0.99	-	-
(3) TRS	Y = 0.617.DEFAPR _(i-1) + 0.044.SURJAN _(i-1) +0.59.PETMAR _(i-1) - 27.1	0.005	2.82	0.92	5.95	0.90
Low-yields season						
(4) CRD	Y= - 0.01.PJAN _(i-1) + 0.11.PAPR _(i-1) - 0.031.POCT _(i-1) + 29.90	0.001	0.04	0.99	-	-
(5) SDS	Y = 0.04.SURJAN _(i-1) + 0.39.PETOCT _(i-1) - 0.104. PFEB _(i-1) + 3.35	0.001	0.05	0.98	-	-
(6) TRS	Y = - 0.45.PETAPR _(i-1) - 0.01.PFEB _(i-1) + 0.04.PMAY _(i-1) - 72.4	0.009	2.07	0.92	3.11	0.96

*i-1 is the second chronological year.

Assad et al., (2004) stated that coffee requires T from 18°C to 23°C to higher yields. T in CE_{MG} was more favourable to yield than SO_{MG} (Figure 3A). The temperatures varied from 22.1 to 23.2°C and from 20.5 to 23.6°C respectively for each region. As the T in CE_{MG} were more favourable, the hydric parameters were selected more often in the models for this region such as P , DEF and SUR (Table 3, Eqs. 1 and 4).

P had a variable influence on coffee production in high-yield seasons in CRD, with $\text{PFEB}_{(i-1)}$ directly correlated with yield, but $\text{PSEP}_{(i-1)}$ was inversely correlated. $\text{PFEB}_{(i-1)}$ is important for the provision of water to the plants during the bud formation, and $\text{PSEP}_{(i-1)}$ was inversely correlated because irrigation is normal in CE_{MG} during this period (Soares et al., 2005) due to the high DEF (Figure 2B). The supply of water was likely higher than necessary, which can also damage the cultivation (Busato et al., 2007). The supply of water above the storage capacity of the soil in $\text{NOV}_{(i-1)}$ also was harmful, because each millimetre of $\text{SURNOV}_{(i-1)}$ decreased yield by an average of 0.034 sacks ha^{-1} (Table 3, Eq. 1).

P also had a variable influence on yield in low-yield seasons in CRD (Table 3, Eq. 4). $\text{PJAN}_{(i-1)}$ and $\text{POCT}_{(i-1)}$ were inversely correlated with yield, demonstrating that excess P at the start of bud formation and during flowering, respectively (Figure 2), was detrimental to yield. $\text{PAPR}_{(i-1)}$ was directly correlated, demonstrating that each millimetre of P increased yield by 0.110 sacks ha^{-1} , probably because bud growth cannot occur in the absence of water.

The agrometeorological models developed in this study forecasted yield well. A general analysis for all locations of the performances of the models, comparing the observed and predicted data for all years (Figure 8), demonstrated highly accurate forecasts, with a minimum R^2_{adj} of 0.889 for TRS in the Cerrado Mineiro region (Figure 8F).

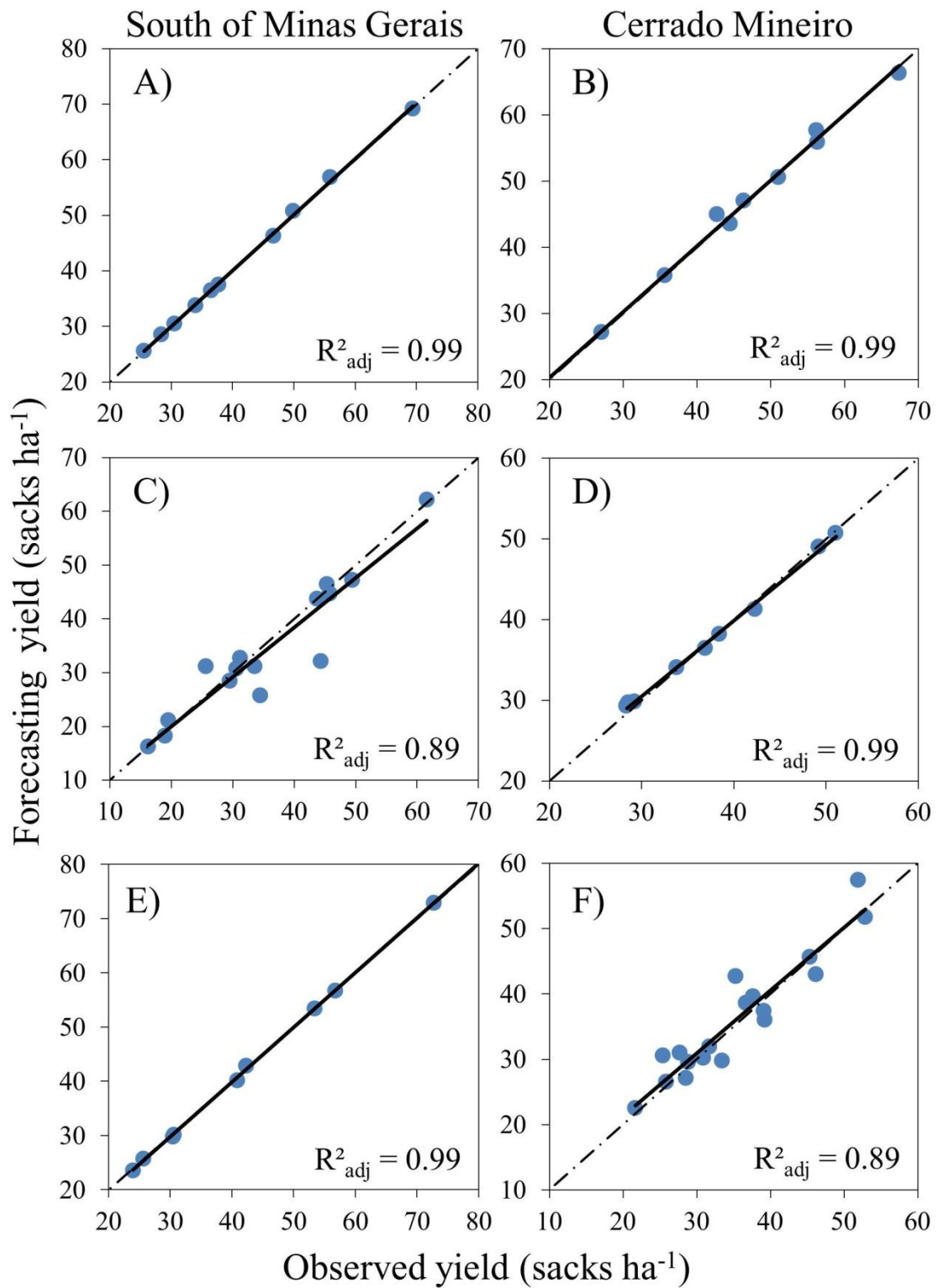


Fig 8. General accuracy of predictions of productivity for regions A) Guaxupé, B) Monte Santo de Minas, C) São Sebastião do Paraíso, D) Coromandel, E) Serra do Salitre, and F) Tiros. Dashed line = line 1:1.

Conclusions

Testing all possible combinations (APC) was efficient for selecting the meteorological parameters and developing the agrometeorological models with multiple linear regressions for predicting the yield of *C. arabica* in the state of Minas Gerais.

The agrometeorological models developed on the basis of meteorological parameters were accurate for all regions. The earliest forecasts before the harvest were six months for Guaxupé in southern Minas Gerais and five months for Coromandel in the Cerrado Mineiro region.

The yield of coffee was controlled by all meteorological parameters in southern Minas Gerais and by hydric parameters in the Cerrado Mineiro region, because the air temperature was generally favourable.

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CAPÍTULO 4 – Climate and natural quality of coffee drink

Abstract: The natural quality (NQ) of a coffee drink is defined as the one that is obtained in the year of bean production with the standard postharvest treatments of a region and thus varies with the climatic conditions during the crop cycle. A well-formed bean can provide a good drink if well processed, but a bean grown during unfavourable environmental conditions will have poor quality regardless of the postharvest options. The goals of this study were to: 1) increase our understanding of the relationship between normal monthly meteorological elements (MEs) and NQ in coffee producing regions, 2) identify the ranges of the MEs during the crop cycle that optimise quality, and 3) develop models to predict NQ based on the MEs. We used the two major regions of coffee production in the Brazilian state of Minas Gerais, the Cerrado Mineiro (CE_{MG}) and southern Minas Gerais (SO_{MG}). We mapped the influences of ME on NQ successfully. Air temperature in November and December for SO_{MG} and precipitation from November to January for CE_{MG} were generally the most important MEs for NQ. Water deficiency, water storage, and rainfall became increasingly more important during winter (June to September) than during other seasons. The crop models were accurate, with errors <7.9% for predicting NQ for all regions. These models used precipitation in June and December, the actual evapotranspiration in May, and the water deficit in April as the MEs for CE_{MG}, and the rainfall in June and December, the water storage in April, and the actual evapotranspiration in May as the MEs for SO_{MG}.

Key-words: agrometeorology, estimation, correlation, *Coffea Arabica* L.

Introduction

Brazil leads world coffee (*Coffea arabica* L.) production (Amarasinghe et al., 2015), but most of the beans produce beverages with highly variable natural drink quality (NQ) (Borges et al., 2002; Brando; Staut, 2012a). The increase in production and quality of coffee from other countries and the increasing demand for special

imported coffees with superior NQ challenges the Brazilian exports in the world market (Silva et al., 2004).

The NQ is determined by a complex combination of flavour and aroma. Flavour has only four classifications (sweet, salty, bitter, and sour), but aroma is more complex, with >44 basic groups composed mostly of phenols, aldehydes, ketones, alcohols, hydrocarbon ethers, carboxylic acids, anhydrous esters, lactones, amines, and sulphurous compounds (Moreira et al., 2001). The beverage contains more aromatic compounds than any other food or drink, with approximately a thousand identified compounds (Holsher et al., 1990). Most of the aroma is due to several volatile compounds produced during bean roasting.

Coffee beans are harvested at the point of highest quality. That quality is determined by environmental and crop-management conditions (Camargo, 1985; Favarin et al., 2004; Custódio et al., 2015). A well-formed bean can produce a good drink, but beans grown under any environmental stress will probably not produce a good drink, regardless of any postharvest treatment (Campa et al., 2004; Favarin et al., 2004; Borém et al., 2008).

Postharvest treatments basically involve the separation of cherry beans from the green and immature beans and drying, peeling (removing the mucilage), and roasting the beans at different temperatures and durations (Favarin et al., 2004; Borém et al., 2008). Bean storage must be as brief as possible to maintain quality, avoiding increases in fatty acids, especially linoleic and palmitic acids, and also avoiding the whitening of the beans (Coradi et al., 2007).

Coffee plants flower multiple times in Central America, Colombia, and eastern Africa where the photoperiod is constant and rains are frequent throughout the year, forcing several selective harvests during the year. The air moisture is constantly high, so the beans must be peeled before drying to avoid acetic fermentation. Beans in Brazil, particularly in Minas Gerais and São Paulo, are first dried in the sun and then peeled and sent to the cooperatives. Sun drying can easily decrease the drink quality due to bacterial fermentation of the mucilage. Good postharvest processing, however, can produce exotic flavours with very distinctive regional characteristics (Martins et al., 2005).

Unfavourable climatic conditions can decrease the accumulation of

photoassimilates, affecting NQ (Fagan et al., 2011). Brando and Staut (2012b) reported that the production of high-quality *C. arabica* is as difficult as the production of fine wine, because it depends on both the experience of the farmers and the dominant climatic characteristics of the region.

NQ is determined by the year of bean production and the standard postharvest treatments of a region, so it depends on the climatic conditions during the crop cycle. NQ in Brazil is normally analysed with a sensorial test called the “cup test”. The beans are also classified according to size, type, and colour following the guidelines of the Brazilian Official Classification (COB), normative number 8/2003 (Brazil, 2003).

NQ depends on the accumulation of carbohydrates, phenolic compounds, and aldehydes during grain development (Fagan et al., 2011), which depends mainly on air temperature and water availability (Damatta; Ramalho, 2006). High temperatures, common at lower altitudes, accelerate grain filling and maturation (Pimenta; Vilela, 2003), which prevents an adequate accumulation of aromatic compounds and consequently decreases the drink quality (Custódio et al., 2007). Low water availability during grain filling causes the malformation of the grains, decreasing their NQ (Fagan et al., 2011).

Excessive rain and consequently high humidity during maturation cause the proliferation of microorganisms that can promote the fermentation of the grain flesh and therefore drastically reduce coffee NQ (Abrahão et al., 2009). To meet the demand of buyers for high quality, the coffee industry must support research that seeks to identify, track (Fagan et al., 2011), and predict the climatic conditions that affect drink quality.

The objectives of this study are to: 1) increase our understanding of the relationships between the normal monthly meteorological elements (MEs) and the natural drink quality of *C. arabica*, 2) identify the ranges of the MEs that optimise quality, and 3) develop models that predict NQ based on the monthly MEs.

Material and Methods

We studied the most important regions of coffee production in Brazil: the

Cerrado region of the state of Minas Gerais (CE_{MG}) and southern Minas Gerais (SO_{MG}) and some areas in the state of São Paulo bordering SO_{MG} (Figure 1). CE_{MG} contains three biomes: tropical grassland, savannah, and seasonal forest (Batalha, 2011). SO_{MG} is a rolling plateau with altitudes ranging from 700 to 1250 m.

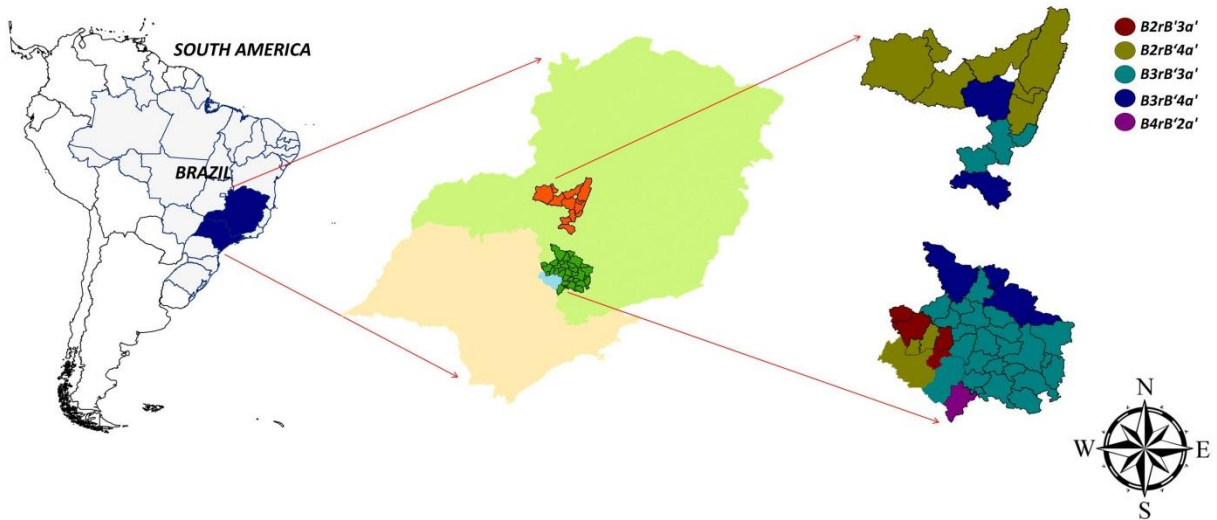


Figure 1. Main regions in the State of Minas Gerais and São Paulo, for coffee production in Brazil.

We collected data for 12, 32, and 7 locations in CE_{MG} , SO_{MG} , and São Paulo, respectively. Coffee plants in CE_{MG} are traditionally irrigated, so to be able to study the effects of climate, we selected municipalities where approximately 40% or fewer of the producers used irrigation. Irrigation is not common in SO_{MG} and São Paulo. The sizes of the farms were about 33 ha in CE_{MG} and 13 ha in SO_{MG} and São Paulo. Plant density was higher in SO_{MG} and São Paulo than in CE_{MG} . The locations in São Paulo were analysed together with those in SO_{MG} (Table 1).

Table 1. Locations in Cerrado (CE) and southern Minas Gerais (SO) used for the assessment of the effect of meteorological elements on the natural quality of coffee drink. The geographic coordinates are expressed in degrees, altitude is expressed in metres, and the climate followed the classification by Thornthwaite (1948).

Locality	Latitude	Longitude	Altitude	Region	Climate*	Locality	Latitude	Longitude	Altitude	Region	Climate*
CAMPOS ALTOS	-19,696	-46,171	1069,38	CE	B3rB'3a'	CARMO DO RIO CLARO	-20,972	-46,119	854,38	SO	B3rB'4a'
CARMO DO PARANAIBA	-19,008	-46,316	912,14	CE	B2rB'4a'	CONCEICAO DA APARECIDA	-21,096	-46,205	985,00	SO	B3rB'3a'
GUIMARÃNIA	-18,844	-46,793	963,26	CE	B2rB'4a'	DIVINOLANDIA	-21,661	-46,739	833,54	SO	B3rB'3a'
MATUTINA	-19,223	-45,969	1005,77	CE	B2rB'4a'	DIVISA NOVA	-21,511	-46,196	867,53	SO	B3rB'3a'
MEDEIROS	-19,996	-46,226	965,89	CE	B3rB'4a'	FAMA	-21,406	-45,829	816,97	SO	B3rB'3a'
PATROCINIO	-18,944	-46,993	946,80	CE	B2rB'4a'	GUARANESIA	-21,299	-46,803	844,24	SO	B2rB'4a'
PRATINHA	-19,751	-46,378	1096,17	CE	B3rB'3a'	GUAXUPE	-21,305	-46,713	945,05	SO	B2rB'3a'
RIO PARANAIBA	-19,194	-46,247	1021,47	CE	B3rB'4a'	ITAMOGI	-21,078	-47,048	989,74	SO	B2rB'3a'
SANTA ROSA DA SERRA	-19,530	-45,966	991,91	CE	B2rB'4a'	JACUI	-21,017	-46,741	1030,47	SO	B3rB'3a'
SAO GOTARDO	-19,311	-46,049	985,62	CE	B2rB'4a'	JURUAIA	-21,253	-46,577	932,00	SO	B3rB'3a'
SERRA DO SALITRE	-19,111	-46,690	964,23	CE	B2rB'4a'	MACHADO	-21,675	-45,920	917,42	SO	B3rB'3a'
TIROS	-19,004	-45,964	869,05	CE	B2rB'4a'	MOCOCA	-21,471	-47,001	645,00	SO	B2rB'4a'
Locality	Latitude	Longitude	Altitude	Region	Climate*	MONTE BELO	-21,326	-46,368	877,77	SO	B3rB'3a'
ALFENAS	-21,429	-45,947	817,42	SO	B3rB'3a'	MONTE SANTO DE MINAS	-21,190	-46,980	905,48	SO	B2rB'3a'
ALPINOPOLIS	-20,864	-46,388	890,27	SO	B3rB'3a'	MUZAMBINHO	-21,376	-46,526	1007,90	SO	B3rB'3a'
ALTEROSA	-21,249	-46,143	836,70	SO	B3rB'3a'	NOVA RESENDE	-21,126	-46,420	1069,93	SO	B3rB'3a'
ARCEBURGO	-21,364	-46,940	696,87	SO	B2rB'4a'	PARAGUACU	-21,547	-45,738	845,50	SO	B3rB'3a'
AREADO	-21,359	-46,146	829,62	SO	B3rB'3a'	PASSOS	-20,719	-46,610	817,75	SO	B3rB'4a'
BANDEIRA DO SUL	-21,728	-46,386	1009,55	SO	B3rB'3a'	POCO FUNDO	-21,781	-45,965	1021,46	SO	B3rB'3a'
BOM JESUS DA PENHA	-21,017	-46,523	1026,65	SO	B3rB'3a'	POCOS DE CALDAS	-21,788	-46,561	1234,02	SO	B4rB'2a'
BOTELHOS	-21,633	-46,395	970,29	SO	B3rB'3a'	SAO JOSE DA BARRA	-20,718	-46,311	800,53	SO	B3rB'4a'
CABO VERDE	-21,472	-46,396	927,21	SO	B3rB'3a'	SAO JOSE DO RIO PARDO	-21,595	-46,887	676,00	SO	B2rB'4a'
CACONDE	-21,528	-46,647	780,00	SO	B3rB'3a'	SAO PEDRO DA UNIAO	-21,127	-46,615	1074,28	SO	B3rB'3a'
CAMPESTRE	-21,711	-46,246	1092,10	SO	B3rB'3a'	SAO SEBASTIAO DA GRAMA	-21,709	-46,821	945,00	SO	B3rB'3a'
CAMPO DO MEIO	-21,107	-45,830	818,82	SO	B3rB'4a'	SERRANIA	-21,548	-46,040	884,69	SO	B3rB'3a'
CAMPOS GERAIS	-21,235	-45,759	844,64	SO	B3rB'3a'	TAPIRATIBA	-21,471	-46,748	760,00	SO	B2rB'3a'

We collected data for monthly normal air temperature (T , °C) and precipitation (P , mm) for all municipalities (INMET, 2009). Potential evapotranspiration (PET) was estimated from T , latitude (ϕ), and Julian day (JD) by the model proposed by Camargo (1971) (equation 1). This model is appropriate for tropical (wet) conditions (Camargo and Camargo, 2000), similar to those described by Thornthwaite (1948) and Penman (1956), and has the advantage of using only one ME (T). The PET is calculated from extraterrestrial solar irradiance (R_o , MJ m⁻² d⁻¹) (equation 2). R_o is function of the relative earth-sun distance (RD) (astronomic units, AU) (equation 3), the solar declination (δ°) (equation 4) and hour of sunrise (hn , °) (equation 5).

$$PET = 0.01 \times R_o / 2,45 \times T \times ND \quad (1)$$

$$R_o = 37.6 \times RD \times \left[\left(\frac{\pi}{180} \right) \times hn \times \sin \Phi \times \sin \delta + \cos \Phi \times \cos \delta \times \sin hn \right] \quad (2)$$

$$RD = 1 + 0.033 \times \cos \left(\frac{360 \times JD}{365} \right) \quad (3)$$

$$\delta = 23.45 \times \sin \left[\left(\frac{360}{365} \right) \times (JD - 80) \right] \quad (4)$$

$$\ln = \arccos[-\tan \Phi \times \tan \delta] \quad (5)$$

where ND is the number of days in the month.

Our goal was to assess the influence of climate on NQ, so we used the climatic water-balance model proposed by Thornthwaite and Mather (1955) to estimate monthly soil-water storage (STO), actual evapotranspiration (AET), water deficiency (DEF), and water surplus (SUR) (Figure 2).

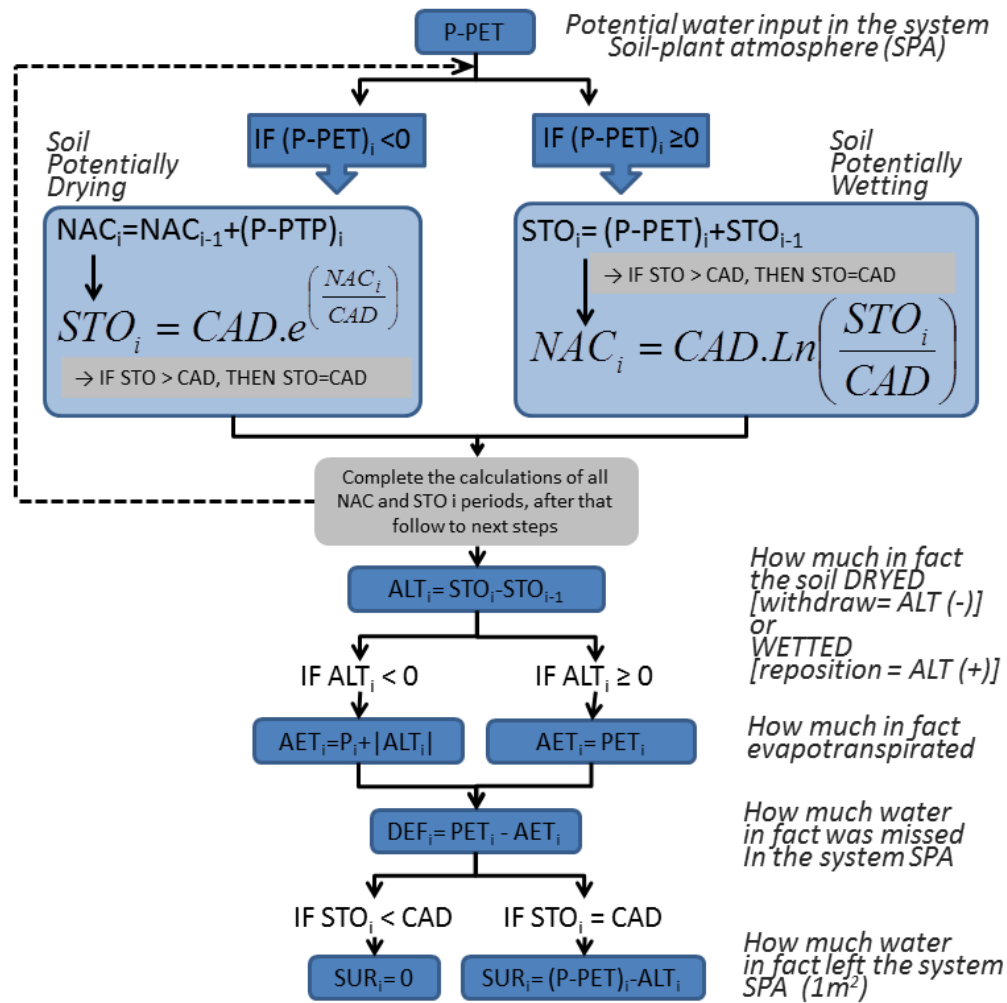


Figure 2. Flowchart of the water balance model modified from Thornthwaite and Mather (1955). Legend: CAD is the soil water capacity (mm), NAC is the negative accumulated (mm), meaning the potential drying of the soil, ALT is the alteration of STO, and i a given period, i-1 previous period.

NQ data were obtained for 2006-2014 from producers and cooperatives in the regions. These data were the number of producers per municipality (F%) that produced coffee with high, medium, and low quality. This general quality classification (Brazil, 2003; SCAA, 2007) is provided by producers for each shipment of coffee delivered to cooperatives. A drink of high quality is called 'soft' to 'very soft' (better), a drink of medium quality is generally 'only soft', and a drink of low quality is 'hard', with some samples 'riadas' (very poor quality). Each producer normally produces various percentages of coffee with high, medium, and low quality in different areas of the farm. Each shipment of coffee is then reclassified into subtypes.

The data were analysed by a correlation matrix between altitude and %F for all regions for a comparison between CE_{MG} and the SO_{MG} , which is generally a simple way to determine the NQs in those regions (Silva et al., 2004). We extended this analysis by classifying the locations by climatic type, following the classification developed by Thornthwaite (1948). This classification summarises the normal hydrological conditions of a region and can efficiently identify regions with the same agricultural potential (Rolim et al., 2007).

A multivariate principal component analysis (PCA) determined the influence on NQ of each weather element (T, P, PET, STO, AET, DEF, and SUR) at each phase of crop development (Manly, 2008). We calculated average T, STO, and %F and total P, PET, AET, DEF, and SUR for each developmental phase (BF is bud formation, BG is bud growth, DOR is dormancy, FLO is flowering, PIN is pinhead (initial formation of grain), GE is grain expansion, GF is grain formation, MAT is maturation and HAR is harvest). The PCA could thus identify the MEs and the phenological phases with the most effect on NQ in the two regions. A univariate correlation (Pearson) analysis provided a more detailed quantification of the relationships between NQ and the MEs for CE_{MG} and SO_{MG} , enabling the analysis of the importance of monthly MEs during the crop cultivation cycle.

We propose a new method for determining the optimal values of the MEs during the phenological cycle. The method has two steps (Figure 3). First, a third-degree polynomial curve is established between a monthly normalised ME setting, corresponding to an independent variable (X), and with quality (%F) as a dependent variable (Y). This setting establish an ideal value for an ME. Measurement statistics,

such as R^2 in this case, are not necessary, because the objective is only to determine the pattern of variation of the relationship.

The second step determines the maximum value of Y (YestMAX) and the standard deviation (SD) for the fitted curve from the first step. The ideal value of X (Xobs) for an ME is $(YestMAX - SD) \leq ME \leq (YestMAX + SD)$. This procedure should be followed for each ME of interest for each month during the crop cycle and for each level of quality. We followed this procedure a total of 483 times (23 (cycle months) $\times$ 7 ME (T, P, PET, STO, AET, DEF, and SUR) $\times$ 3 quality levels (high, medium, and low)). This method determines the range of the fitted curve that maximises Y (the quality in this case), allowing the determination of the optimal monthly ranges of T, P, PET, STO, AET, DEF, and SUR for maximising each level of NQ in CE_{MG} and SO_{MG} .

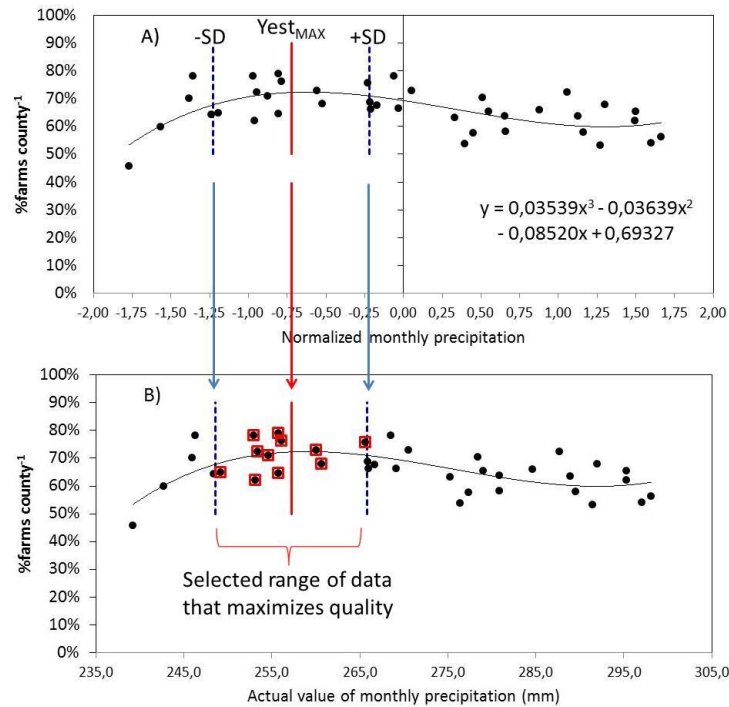


Figure 3. Method for determination of optimal ranges of values of the meteorological elements. A) Step 1: standardization of meteorological data and setting of a third-degree polynomial curve, B) Step 2: selection of the original values of the meteorological element that maximizes quality.

The relationship for each ME in each growth stage will be the basis for the development of crop models for estimating NQ using multiple linear regression. The dependent variable (Y), i.e. NQ, and the independent variables (X_n), i.e. the 84

monthly MEs (7 MEs $\times$ 12 months) (Equation 6), were run for each quality level (high, medium, and low). Months in which the ME values and multicollinear variables did not change were removed from the analysis, reducing the average total of the most important independent variables for each municipality to 67.

The elimination of multicollinear variables is the first step in this model (Gujarati; Porter, 2011). Multicollinearity causes a shift in the slope coefficients, preventing their analysis. A correlation matrix was thus constructed for the monthly MEs. The variables with $r > 0.7$ were tested separately in the models:

$$Y = \beta_1 \times X_1 + \beta_2 \times X_2 + \beta_3 \times X_3 + \dots + \beta_o \quad (6)$$

where β_n are the slope coefficients, and β_o is the linear coefficient

All MEs are important, but we analysed models with up to five independent variables. The challenge was thus to select the independent variables that produce the lowest errors. The analysis was multivariate because the combination of the variables was important for this minimisation. Several methods are available for selecting independent variables for linear and non-linear models (Xu; Zang, 2001): a) forward selection (stepwise), b) backwards elimination (stepwise), c) leaps-and-bounds regression, d) orthogonal descriptors, e) genetic algorithms, f) genetic populations, g) choosing the operators, and h) fitness evaluation. These methods basically identify calculation errors associated with the insertion or removal of variables in a model. The methods, however, do not test all possible combinations of alternatives and determine only if the insertion (or removal) of a new variable decreases the previous error. The stabilisation of local errors, not finding the best design, is the weakness of these numerical methods. Despite the long computational times, we decided to test all possible combinations (APC), thereby analysing all domain groups and identifying the best models. For each municipality, we tested on average 67, 2211, 47 905, 3 766 480, and 9 657 648 models with 1, 2, 3, 4, and 5 independent variables, respectively, totalling 10 474 311 models.

The best models were selected based on a statistical index of accuracy, the mean absolute percentage error (MAPE), and an index of precision, the adjusted coefficient of determination (adjusted R^2) (equations 7 and 8), considering only

regressions statistically significant by an F test ($p < 0.05$):

$$MAPE(\%) = \frac{\sum_{i=1}^n \left(\left| \frac{Y_{est_i} - Y_{obs_i}}{Y_{obs_i}} \right| \times 100 \right)}{n} \quad (7)$$

$$R^2_{adjusted} = \left[1 - \frac{(1-R^2) \times (n-1)}{n-k-1} \right] \quad (8)$$

where Y_{est_i} is the estimated percentage of producers per municipality in year i , Y_{obs_i} is the observed percentage of producers per municipality, n is the number of datapoints, and k is the number of independent regression variables.

Results and Discussion

CE_{MG} and SO_{MG} produced high-quality coffees (Figure 4). More than 66% of the farms by municipality (%FM) belonged to this category. CE_{MG} , however, had 10% more %FM than SO_{MG} . SO_{MG} had a more variable distribution of quality than CE_{MG} , probably due to the higher variability of the relief that leads to a higher variability of microclimates. A %FM of less than 5% in CE_{MG} produced low-quality coffees (Figure 4), but the %FM in SO_{MG} was as high as 12% of the locations due to the higher variability of the relief.

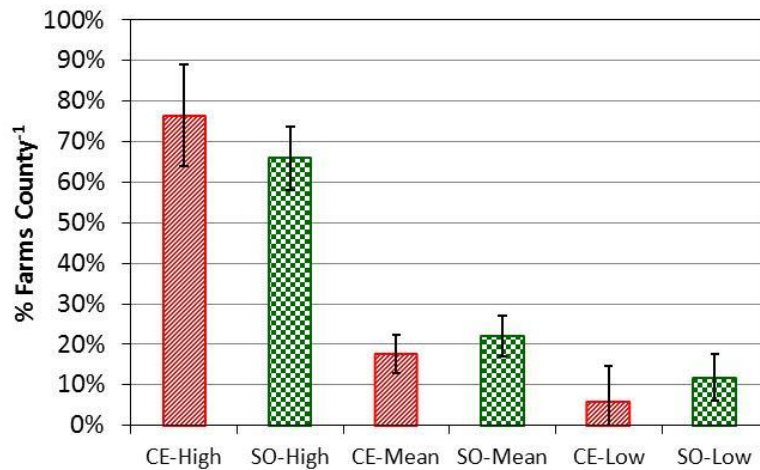


Figure 4. Distribution of the number of localities with high, medium and low quality at regions of the Cerrado (CE) and South of Minas Gerais (SO).

Our understanding of the influences of climate on NQ is not yet complete. Silva (2010) concluded that coffee plantations at altitudes >700 m in the Mogiana region of São Paulo have an advantage of higher grain quality, but rain during

ripening is harmful to quality. The authors also suggested that adverse temperatures during maturation may adversely affect NQ. Camparotto (2012) developed an agrometeorological model to identify the climatic potentials for the successful production of high-quality coffees in São Paulo.

The altitude at which coffee is planted has traditionally been an indicator of potential quality worldwide. In our study, the production of good drink increased with altitude with a decrease in medium- and low-quality coffees in all regions. The altitude was positively correlated ($r = 0.67$) with %FM and with high-quality beverages in CE_{MG} (Figure 5A). The correlation was similar ($r = 0.68$) for average NQ but was negative, indicating that average quality decreased with increasing altitude. CE_{MG} was characterised by a %FM of <7% that produced low-quality coffee, regardless of altitude. SO_{MG} had similar correlations with %FM and altitude as CE_{MG} (Figure 5B).

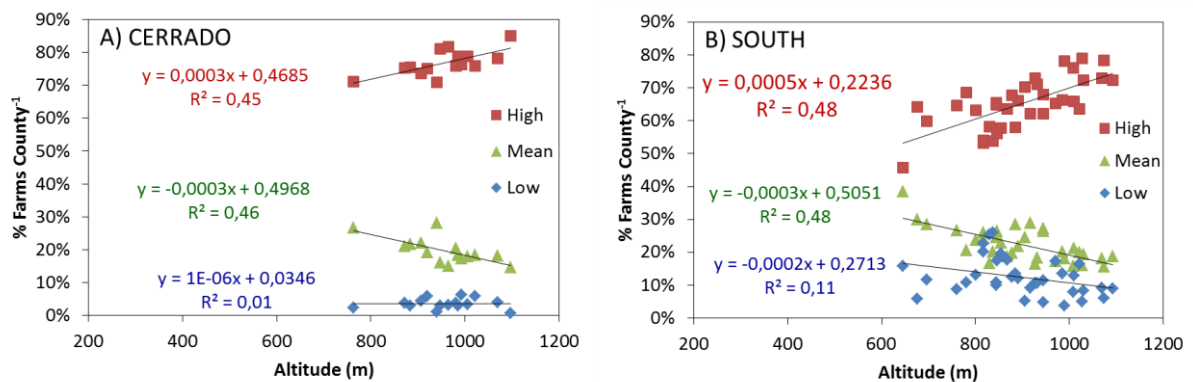


Figure 5. Correlation between the percentage of producers by municipality (%FM) and altitude to the regions of the Cerrado Mineiro (A) and southern Minas Gerais (B), State of Minas Gerais.

We applied the climatic classification of Thornthwaite (1948) to all municipalities and then analysed %FM for each climatic type to determine the influence of climate on NQ (Figure 6). The climatic types of the classification from the hottest and driest (megathermal) to cooler and more humid (mesothermal) were B₄rB'₂a', B₃rB'₄a', B₃rB'₃a', B₂rB'₄a', and B₂rB'₃a' (Figure 6). CE_{MG} is cool and wet, and increased high NQ and decreased medium and low NQ. The amount of fine coffees in SO_{MG} varied little with climate, but average NQ increased and low NQs decreased with the cooler, more humid climates.

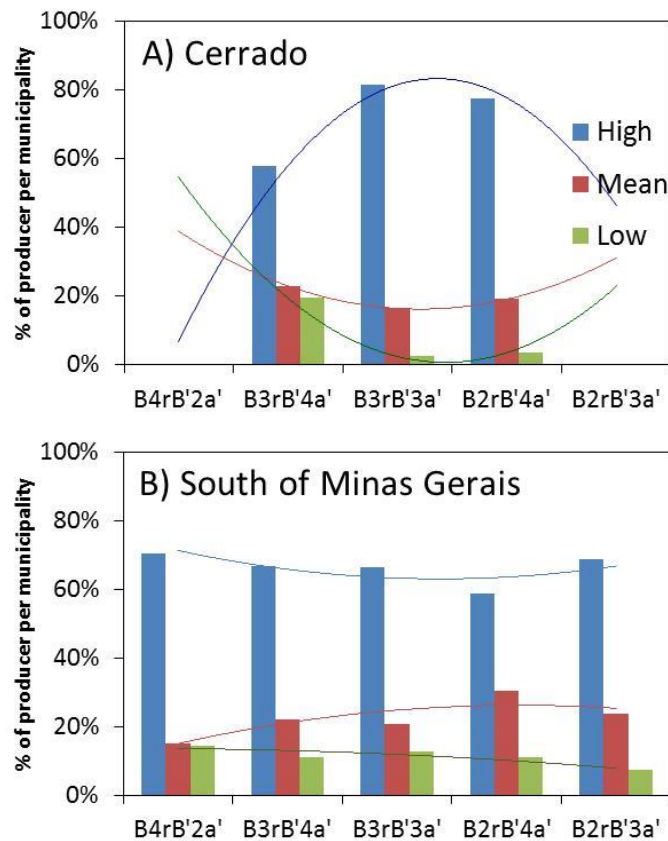


Figure 6. Percentage of producers by municipality with high quality coffees, medium and low for the Cerrado region (A) and the South of Minas Gerais (B) in relation to climatic types of Thornthwaite (1948).

We conducted a PCA to determine the influence of climate in each phenological phase on NQ. Precipitation during vegetative growth (P_{VG}) had the largest negative influence on quality in areas of CE_{MG} (Figure 7A) and SO_{MG} (Figure 7B). Intense vegetative growth one year will decrease coffee production the next year due to coffee's two-year production cycle (biannuality) (Pereira et al., 2011).

STO, PET, and AET were also important variables during the phase of vegetative growth (VG) and were negatively correlated with quality in both CE_{MG} and SO_{MG} . Rainfall during bud formation (BF), grain expansion (GE), and grain filling (GF) were also negatively correlated with quality, indicating that plants with proportionally less fruit and smaller grains provided higher qualities. DEFs during BF, the pinhead phase (PIN), GE, and GF were positively correlated with quality. DEFs during BF, PIN, GE, and GF favour the reduction of gems, the dropping of pinheads (November drop), less fruit expansion, and less fruit formation, respectively (Damatta; Ramalho,

2006), increasing the quality of the remaining grains.

Water availability differed between CE_{MG} and SO_{MG} , especially SUR. SURs during GE and BG were important only in CE_{MG} and SO_{MG} , respectively. SUR_{GE} was important in both regions due to summer rains from November to January; SUR_{BG} from April to June each year represented the second rainiest season.

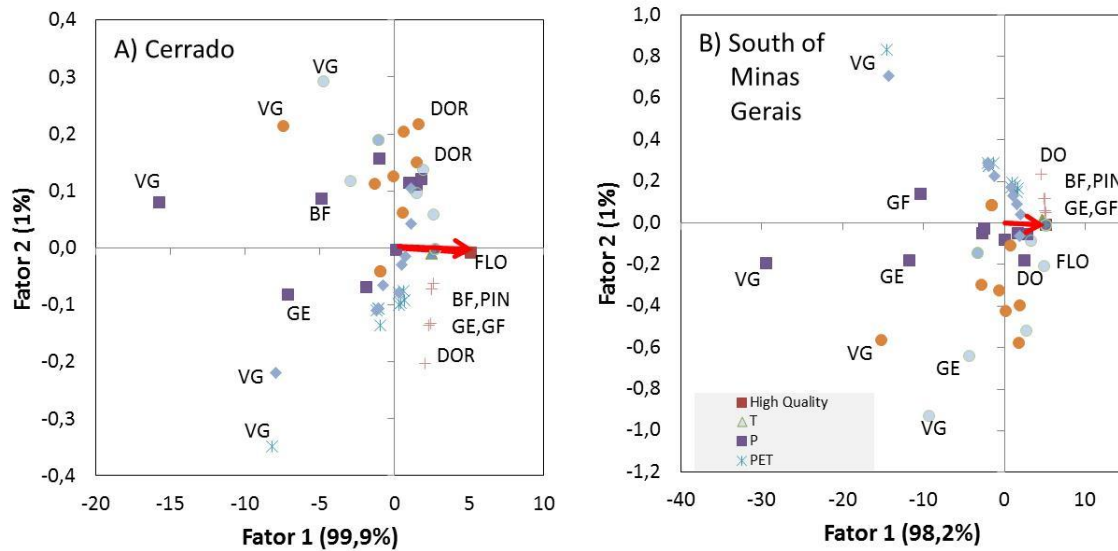


Figure 7. Multivariate principal component analysis (PCA) taking into account all the monthly data of air temperature (T), precipitation (P), potential evapotranspiration (PET), actual evapotranspiration (AET), soil water storage (STO), water deficit (DEF) and water surplus (SUR) integrated in each phenological phases for all the municipalities of A) Cerrado and B) in Southern Minas Gerais. Legend: the arrow indicates the quality of component (percentage of producers by municipality with high quality), VG: vegetative growth, BF: bud formation, BG: bud growth, DOR: dormancy, FLO: flowering, PIN: pinhead, GE: grain expansion, GF: grain formation, MAT: maturation and, HAR: harvest

The monthly correlation analysis indicated a highly variable and complex influence of ME on coffee quality (Figure 8). T was the most important ME in every month, mainly in SO_{MG} (Figure 8B). T was more important in November and December (summer) and less important in June and July (winter). Other variables such as DEF and STO increased in importance when T was less influential in winter. PET, calculated based on T, was also important. SUR was important from October to April (Figure 8). P was the most important variable in every month in CE_{MG} , mainly

from November to January. The five highest correlations with quality in CE_{MG} were P_{JUN} , AET_{JUN} , P_{MAY} , P_{DEC} , and SUR_{JUL} , with r of -0.66, -0.66, -0.56, 0.53, and 0.53, respectively. The highest correlations in SO_{MG} were PET_{JAN} , PET_{FEB} , T_{FEV} , T_{JAN} , and T_{MAR} , with r of -0.60, -0.59, -0.585, -0.581, and -0.58, respectively (Figure 8).

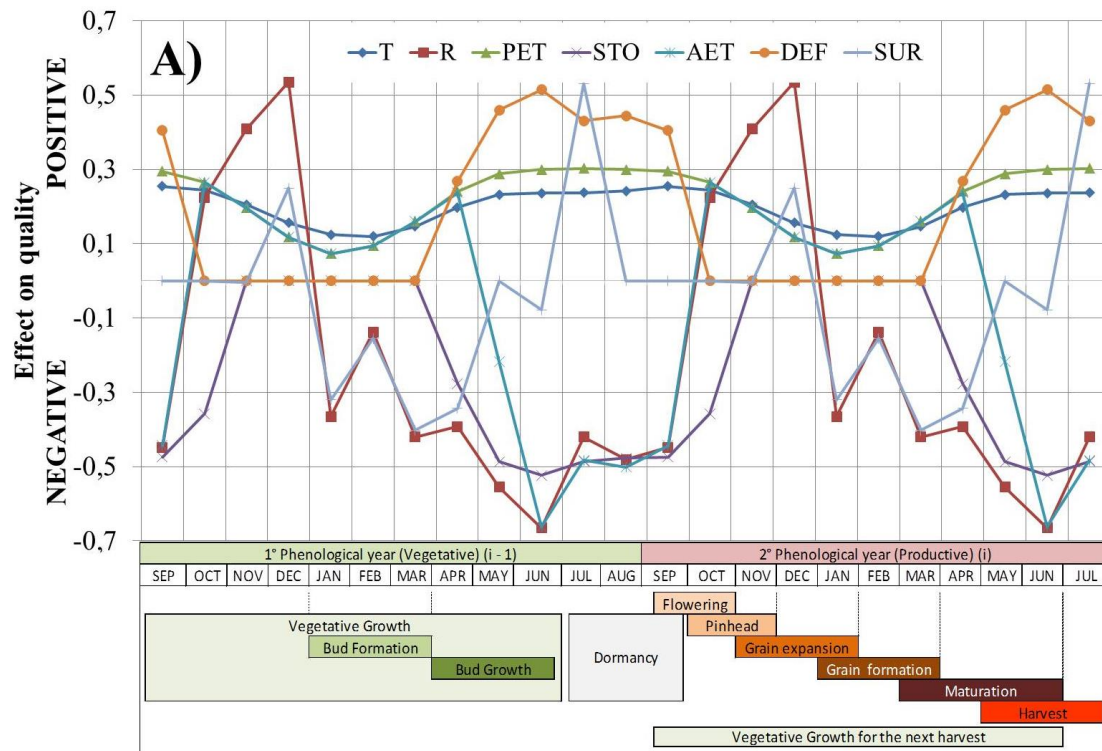
The highest correlations with quality in CE_{MG} were P_{NOV} , P_{DEC} , P_{MAY} , and P_{JUN} , with P_{NOV} and P_{DEC} correlated positively and P_{MAY} and P_{JUN} correlated negatively. P_{NOV} positively affected VG, PIN, and the beginning of GE, and P_{MAY} and P_{JUN} adversely affected BG and MAT. Abrahão et al. (2009) also reported that high rainfall during ripening decreased NQ. The highest correlations with quality in SO_{MG} were from P_{JAN} to P_{MAR} , which positively affected quality because they coincided with BF and GF. P_{JUN} and P_{JUL} were negatively correlated with quality, affecting late BG and the beginning of DP, after the final period of MAT and HAR.

All MEs had influences in FLO in CE_{MG} and SO_{MG} except SUR. DEF, PET, and T in CE_{MG} , however, were positively correlated with quality, but AET, P, and STO were negatively correlated. These correlations indicated that little rain, a water deficit, and high temperatures in September are required for flowering to provide high NQ. All MEs in SO_{MG} were negatively correlated with quality, indicating that little rain, a water deficit, but low temperatures are required for good flowering in September. Fernandes et al. (2012) reported similar findings.

DEF was important from April to September in CE_{MG} and SO_{MG} , with the exception of August in SO_{MG} (Figure 8 and 9). DEF in CE_{MG} was positively correlated with quality, indicating that the lack of water during BG, DOR, FLO, MAT, and HAR favoured quality. DEF was negatively correlated with quality in SO_{MG} , indicating that the lack of water in BG, DOR, FLO, MAT, and HAR decreased quality. The conditions in CE_{MG} were opposite to those in SO_{MG} from the beginning of GF in January to HAR in June. T and PET in CE_{MG} were positively correlated with quality, and P and SUR were negatively correlated, perhaps because T was higher in CE_{MG} than SO_{MG} (Figures 8 and 9).

AET had higher variation of correlations in CE_{MG} than SO_{MG} , due to higher variation of correlations of STO and DEF in CE_{MG} . AET_{JUN} was most correlated with quality in CE_{MG} , corresponding to BG, the end of MAT, and early HAR. The highest correlation for AET in SO_{MG} occurred from January to March (summer),

corresponding to BF and GF. The sum (absolute value) of the monthly correlations provides a parameter for identifying the months when NQ is most sensitive to climatic variability (Figure 10). NQ was most sensitive from May to September in CE_{MG} and from March to June in SO_{MG} .



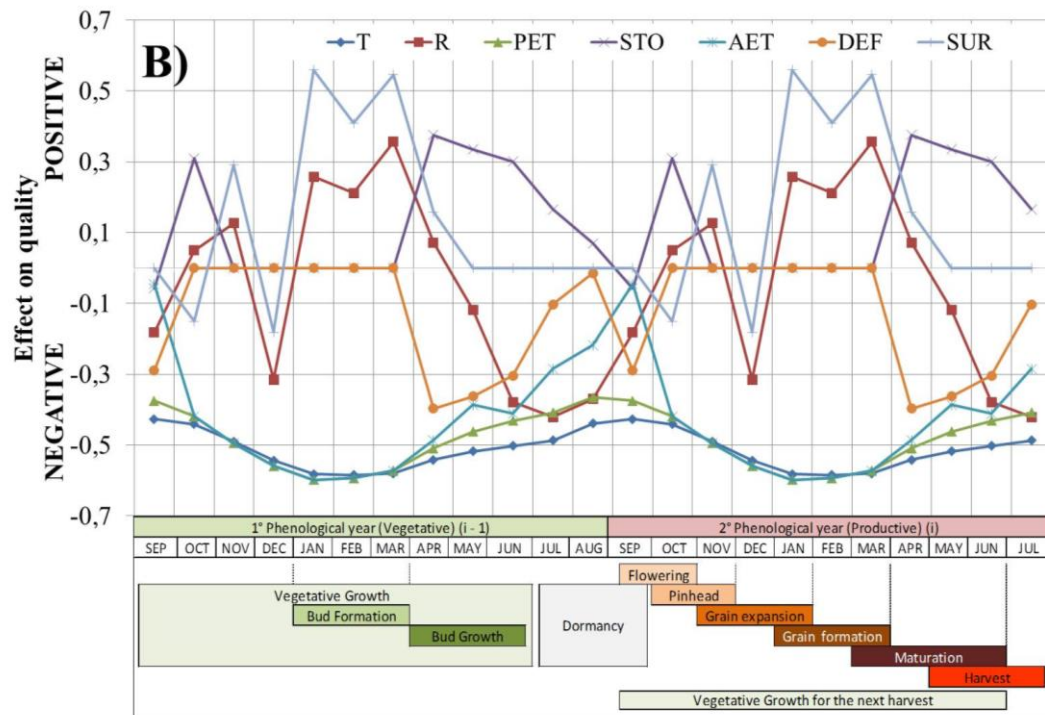


Figure 8. Monthly correlations between meteorological elements and the coffee quality drink for the region A) Cerrado and B) South of the State of Minas Gerais. Symbols: SUR: water surplus, DEF: water deficit, STO: soil water storage, R: rainfall, T: air temperature.

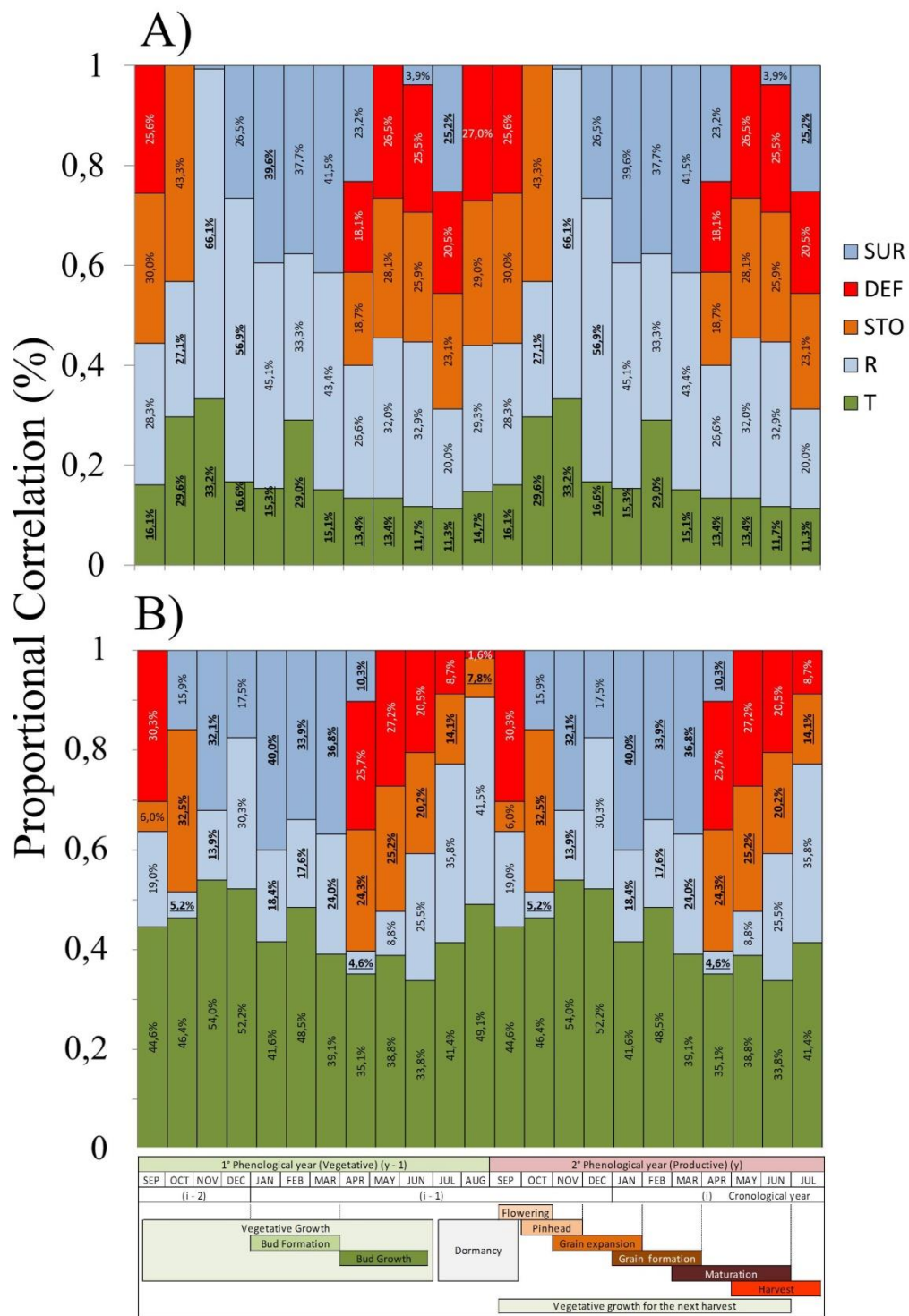


Figure 9. Ratio between the monthly correlation of meteorological elements with the drink quality (high) to A) Cerrado and B) South of Minas Gerais State. The underlined and bold percentages are positive correlations and the plain percentages represent negative correlations with quality. Symbols: SUR is water surplus, DEF is water deficit, STO is soil water storage, R is rainfall and, T is air temperature.

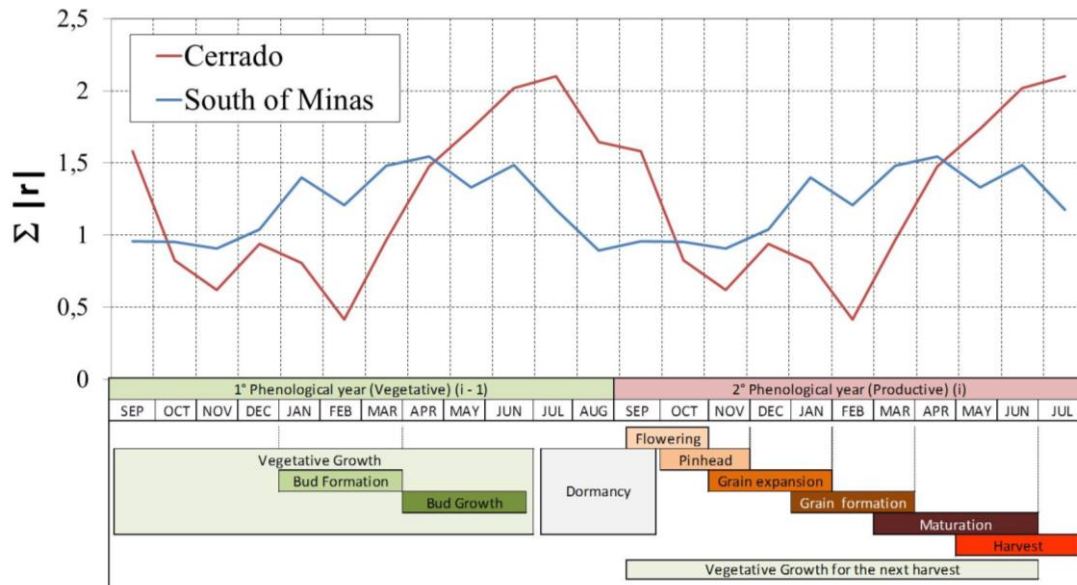


Figure 10. General climate influence on coffee expressed by the sum module monthly correlations (air temperature, precipitation, water storage in soil, deficit and surplus water).

The method developed to optimise the monthly MEs was robust, because we always selected the values that maximised %FMs for high, medium, and low quality in various situations. The determination of January temperatures for coffee plantations in SO_{MG} (Figure 11) is an example of this optimisation. This method allowed us to determine that air temperatures of 19.5-21.2 °C in January maximised the number of producers with high-quality coffees (Figure 11A). Temperatures higher than 21.2 °C maximised the number of producers with medium and low-quality drinks (Figure 11B and C).

This method was also used for all other months for determining the optimum ranges of T, P, PET, STO, AET, DEF and SUR for SO_{MG} and CE_{MG} (Figures 12 and 13). The optimal T in July, for example, should be between 13.5 and 15 °C for maximising %FM in the high-quality range in SO_{MG}. The higher the temperature in July and October in SO_{MG}, the larger the decrease in high quality (Figure 12A). March, May, August, and October were more restrictive in CE_{MG}, when the Ts should be around 21.7, 16.8, 17, and 20 °C, respectively (Figure 12B). The optimal P in August ranged from 31 to 43 mm in CE_{MG} but only from 5 to 18 mm in SO_{MG}. Note that a higher DEF in August favoured quality in CE_{MG} but decreased it in SO_{MG}.

(Figure 13E and F).

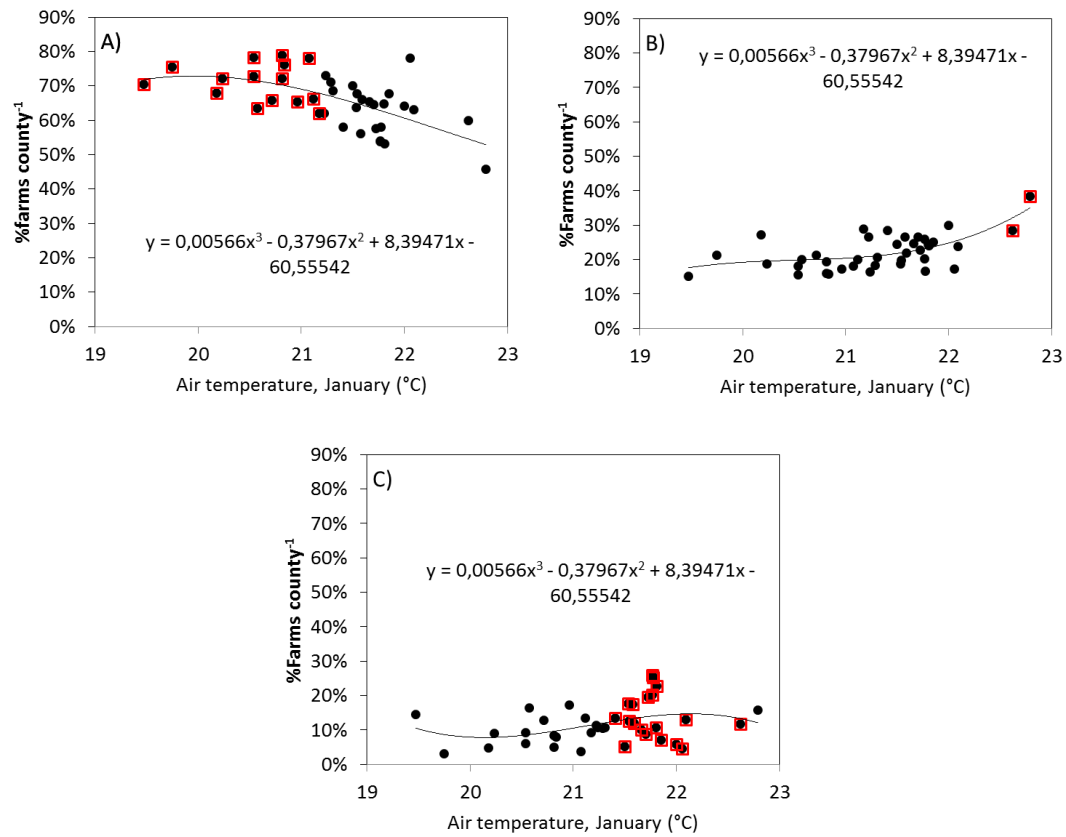


Figure 11- Example of polynomial adjustment of the method of third degree for selecting the range of optimal values of meteorological elements for percentage of local municipalities by A) High, b) Average and C) Low natural quality coffee beverage in South Minas Gerais in January. Legend: round data points observed, square dots selected data. The optimal precipitation ranges were narrow because this study used normal data very nearby regions, especially in southern mines (Figure 11.C and 12.D). The CE_{MG} is ideal that the rains are interrupted between May and October to increase the quality of drinking.

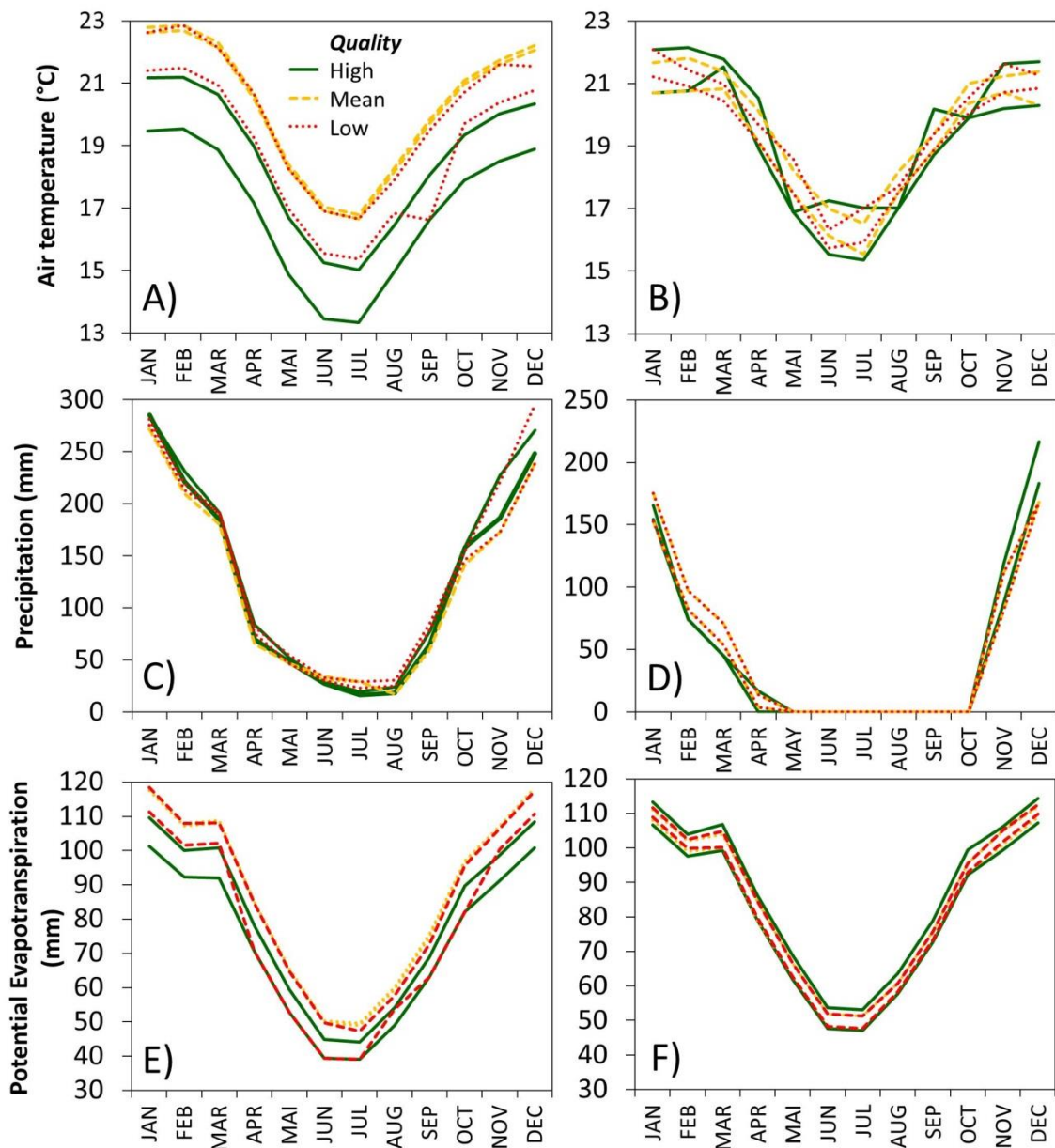


Figure 12. Ideals ranges of the monthly meteorological elements: air temperature (A, B), rainfall (C, D), potential evapotranspiration (E, F). Each pair of curves represents the maximum and minimum values found in the municipalities to obtain high, medium and low quality of coffee natural drinks in the Cerrado and South of Minas Gerais.

The ideal range to the CE_{MG} August can range from 31 mm to 43 mm and in the SO_{MG} between 5 and 18 mm only. Note that when there is DEF higher in August in the cerrado quality is favored, while in the south of high set mines disfavor quality (Figure 13.E.F).

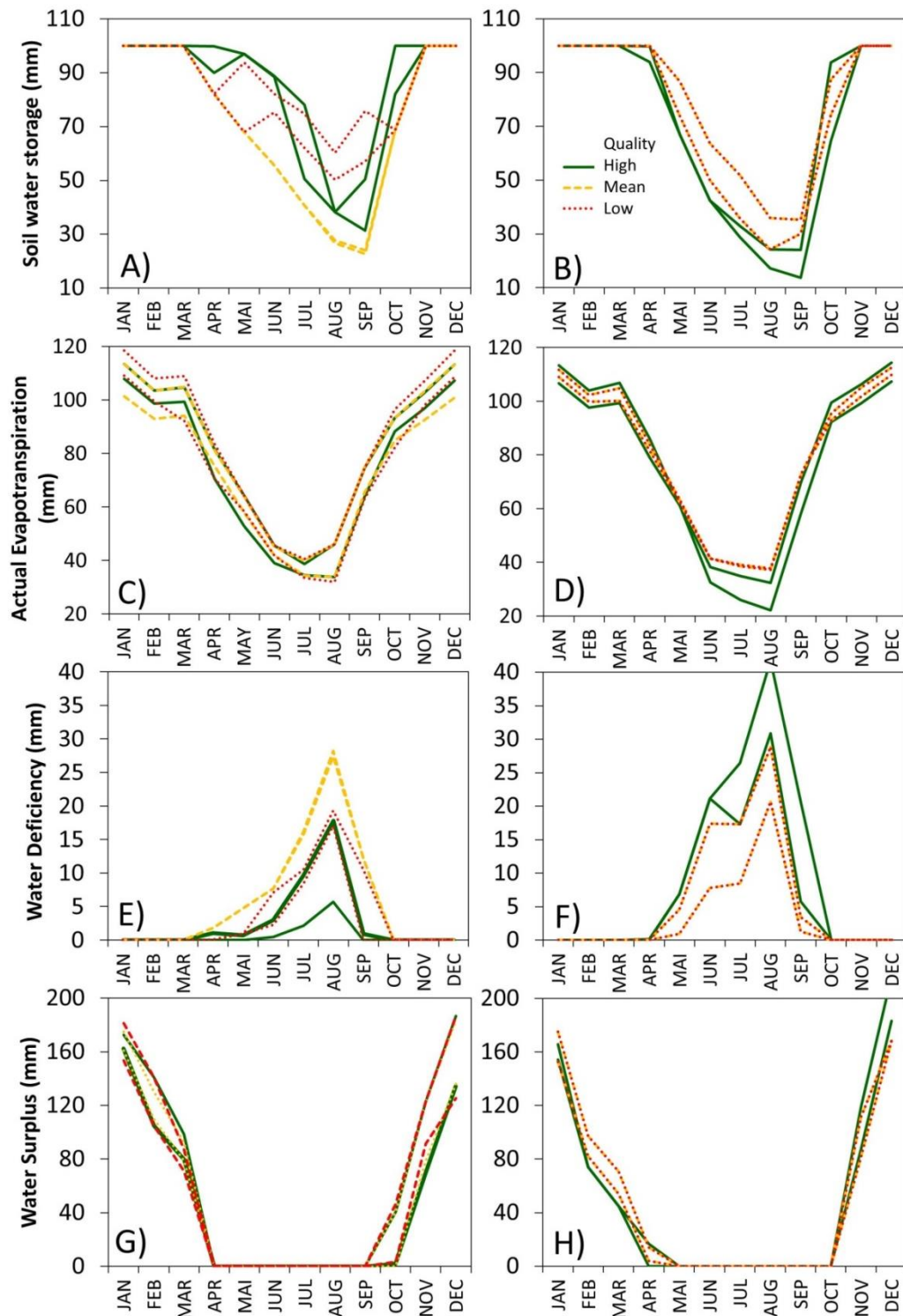


Figure 13- Ideals ranges of the monthly meteorological elements: water storage in the soil (A, B), actual evapotranspiration (C, D), water deficit (E, F) and water surplus (G, H). Each pair of curves represents the maximum and minimum values found in the municipalities to obtain high, medium and low quality of natural drinks in the South of Minas Gerais and Cerrado Mineiro.

The correlation matrix identified the variables that should be removed first from the models. This elimination is important because multicollinearity induces a shift in the adjusted angular coefficients, which does not allow an analysis of the monthly climatic influences for determining the NQ. There was collinearity between P_{JAN} and SUR_{JAN} variables P_{FEV} and P_{MAR} , DEF_{MAI} and DEF_{SET} . The APC method produced equations 9 and 10 that could estimate the %FMs producing high-quality coffees in CE_{MG} and SO_{MG} , respectively.

$$\%F_{CE} = -0,03755 \times P_{JUN} + 0,00066 \times P_{DEC} - 0,11563 \times AET_{MAY} - 0,47694 \times DEF_{APR} + 8,21118 \quad (9)$$

$$\%F_{SO} = -0,01393 \times P_{JUN} - 0,00232 \times P_{DEC} + 0,010026 \times STO_{APR} - 0,01246 \times AET_{MAY} + 1,4851 \quad (10)$$

The models for CE_{MG} and SO_{MG} produced a MAPE and adjusted R^2 of 5.7 and 0.73% and 0.62 and 7.9%, respectively, and were significant at 99% probability. The most important variables in both models were for May, April, June, and December. These periods corresponded (Figure 10) to BG, GE, MAT.

DEF_{APR} was the most sensitive variable calibrated in the first model (equation 9) and was negatively correlated with quality. The model output confirmed that water deficiencies during the ripening period were favourable for quality. Every 100 mm of DEF in April decreased by 47% the average number of producers by municipality that would produce high-quality coffees. P_{JUN} was the most important variable in the second model (equation 10) and was also negatively correlated with quality, indicating that rainy periods during maturation and harvest greatly decreased the quality of coffee in SO_{MG} . Damatta and Ramalho (2006) reported similar results.

Conclusions

Relationships were identified between monthly meteorological elements and the natural quality of coffee drink. The most important meteorological elements were air temperature in November and December in southern Minas Gerais and precipitation from November to January in Cerrado.

The relationships between the meteorological elements for each phenological phase were diverse. The ranges of monthly values for each meteorological element

indicated that higher temperatures, lower precipitation, lower soil-water storage, and higher water deficits were needed in Cerrado than in southern Minas Gerais for producing high-quality coffees.

The models developed were accurate, with errors <7.9%. The most important meteorological variables for the models were precipitation in June and December, actual evapotranspiration in May, and water deficit in April for the Cerrado region of Minas Gerais and precipitation in June and December, water storage in April, and actual evapotranspiration in May for southern Minas Gerais.

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