A New Approach for Analyzing and Interpreting Data on Fruit Drop in Mango

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Abstract. Mango yields are frequently reduced by premature fruit drop, induced by plant stresses during the fruit set period in response to unsuitable climatic or crop management conditions. There are varying strategies for assessing premature fruit drop, which render the comparison and interpretation of published data difficult to draw general conclusions. Therefore, the objective was to provide a mathematical model that is generally valid for describing fruit losses of mango. The model was tested and validated by monitoring the fruit drop for the two local North Vietnamese cultivars, Hôi and Tròn, in different management systems over six consecutive growing seasons: 1) mango–maize intercropping and mango monocropping; 2) irrigation; and 3) plant growth regulator applications with 10 ppm N-(2-chloro-4-pyridyl)-N'-phenylurea (CPPU), 40 ppm 1-naphthaleneacetic acid (NAA), and 40 ppm gibberellins (GA₃ and GA₄₊₇). The timely pattern of fruit drop was best described with a sigmoid function ($r^2 = 0.85$) and formed the basis for defining three distinct drop stages. The post-bloom drop, from full bloom to the maximum daily rate of fruit drop [FD(x)], had the highest fruit losses. The following midseason drop stage ends at 1% FD(x), a threshold that is suggested after a comprehensive literature review. Thereafter, during the preharvest drop stage, treatment and cultivar differences appear to remain constant despite continued fruit drop. In contrast to other mango intercropping studies, fruit loss was not greater in the mango–maize intercropping than in the mango monocropping. Irrigation resulted in approximately three times higher fruit retention compared with the non-irrigated control. A single application of NAA at marble fruit stage (BBCH-scale 701) resulted consistently in the highest fruit retention for both cultivars in midseason and at harvest. The model permits the separation between the drop stages, thus allowing the evaluation of 1) natural variation before treatment effects during post-bloom drop; 2) treatment efficacies during midseason drop; and 3) yield forecasting at the beginning of the preharvest stage.

The worldwide production of mango (*Mangifera indica* L.) is frequently reduced by severe losses of fruit numbers throughout the growing season, a phenomenon that is referred to as premature fruit drop (Singh et al., 2005).

Mango produces an abundance of male and polygamous flowers, but only a small proportion of the latter group is successfully pollinated and has the potential for setting

fruit (Mukherjee, 1953; Singh et al., 1966). Numerous abiotic and biotic factors reduce pollen viability (Issarakraisila and Considine, 1994), the fertilization process of the flower, and embryo survival (Lakshminarayana and Aguilar, 1975), which are all commonly associated with extensive fruit drop in early season (Singh et al., 2005). Fruit that remains attracts a greater share of the available tree resources for continued growth and development. Subsequent fruit drop is induced by any factor reducing carbohydrate availability and thus the demand of the growing fruit is not sufficiently matched by its supply (Wünsche and Ferguson, 2005). This carbohydrate imbalance can occur, for example, by air temperatures below 13 °C or exceeding 36 °C as a result of heavily reduced leaf photosynthesis rates (Issarakraisila and Considine, 1994; Whiley et al., 1999; Yamada et al., 1996).

For mango, principal phenological growth stages are distinguished (Hernández Delgado et al., 2011) according to the general BBCH-scale (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie); however, fruit drop is only described in Stage 7 with “beginning and end

of the physiological fruit drop” when fruits have attained 10% or 30% of final fruit size, respectively. The premature fruit drop stages have been named invariably and there is also no common agreement on the number of drop stages as well as the onset and duration of each. Dahshan and Habib (1985) originally described three distinct stages of premature fruit drop of mango and this classification was also used in the review of Singh et al. (2005). The first stage is referred to as “post-setting drop” and ceases 60 d after “fruit set” (BBCH-scale 619). The second stage is termed “mid-season drop,” characterized by a duration of 15 d with lesser intensity than during the “post-setting drop.” The third stage is the “pre-harvest drop” with only moderate losses.

These descriptions of premature fruit drop, commonly found in the literature, represent some considerable limitations. The onset of each fruit drop stage is based on a “fixed” number of days from “fruit set” as used for example in the review of Singh et al. (2005). Fruit set, however, is variably related to: 1) time after all flowers have dried out at the end of bloom (Malik and Singh, 2003); 2) 14 d after full bloom (DAFB) (Notodimedjo, 2000); or 3) size of fruitlets (Lam et al., 1985). The flowering of mango is a very prolonged and sometimes non-synchronized process, especially in the tropics where erratic flowering is common but also in the subtropics flowering can occur from a few days of an individual flower, 1 to 2 weeks within a panicle to up to 1 month within a tree canopy (Goguet, 1997; Mukherjee, 1953; Verheij, 1986). Typically, panicles exhibit a hierarchical flowering pattern from distal to proximal with an overlapping continuum of flowering and fruit development (Mukherjee, 1953; Singh, 1954). The terms “full bloom” and “fruitlet size” are often subjectively assessed by scoring and variably defined and thus do not offer precise occurrences that justify a valid comparison of published fruit set data. The duration of each fruit drop stage is clearly dependent on seasonal, regional, and cultivar-specific variability and therefore the “fixed time after fruit set” definition might be useful for characterizing the annual drop pattern of a given cultivar in one location but is not appropriate when comparing multiple data sets. Consequently, the main objective of this study is to provide a new approach for interpreting and evaluating fruit drop data, attempting to overcome or at least to alleviate the limitations described. Consequently, fruit drop of two mango cultivars was monitored in largely different cropping and management systems over six seasons in the Province Sơn La in North Vietnam and data were tested and validated in a mathematical model.

Unfavorable environmental cues, particularly when temperature extremes coincide with severe drought conditions (Elsheery et al., 2007), are thought to be key triggers for the extensive premature fruit drop patterns in this province. Huang (2010) further suggested poor orchard management, in particular insufficient pest management, as an

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additional cause of fruit drop for the local mango cultivars Hôi and Tròn predominantly cultivated in this region.

Despite extremely low orchard productivity of $\approx 1 \text{ t} \cdot \text{ha}^{-1}$ (Yên Châu, 2008, Statistical Data of Yên Châu District, Statistical Department, unpublished data), mango trees are often planted either in monoculture or in intercropping systems with mainly maize in the mountainous Province of Sơn La with steep, sloping hillsides. Indeed, tree crops, including mango, provide a more appropriate and sustainable land use system for steep, deforested slope sites (Roberts-Nkrumah, 2000; Young, 1989), because the cultivation of annual crops in monocropping systems under those topographical conditions will lead to reduced soil fertility and severe soil erosion (Clemens et al., 2010). In particular during the juvenile phase of tree crops, intercropping with annuals is a common practice (Musvoto and Campbell, 1995; Roberts-Nkrumah, 2004). However, it has been reported that some plant species enhance mango fruit drop in intercropping systems (Singh et al., 2005).

Crop management strategies such as irrigation or plant growth regulator (PGR) applications may also offer opportunities for fruit drop prevention. Galán Saúco (1997) suggested that the water requirement of mango is $\approx 100 \text{ mm}$ monthly during the fruit development period to ensure good productivity. However, this level is typically lower during early fruit development in the Province of Sơn La (Roemer et al., 2011) with water deficiency particularly prevalent from bloom to midseason drop as a result of the lack of precipitation or irrigation sources. Alternatively, applications of PGRs are commonly used for enhancing fruit retention in many perennial fruit crops, including mango. For example, CPPU increased fruit retention in different mango cultivars and growing regions (Burondkar et al., 2009; Notodimedjo, 2000). Similar effects were shown when GA was applied either alone or in combination with other PGRs (Benjawan et al., 2006; Chen, 1983; Notodimedjo, 2000; Oosthuysen, 1993, 1995; Ram, 1983; Singh, 2009). Moreover, the synthetic auxin NAA is another fruit drop-reducing PGR with a timely different efficacy; fruit retention is less affected when applied around post-bloom rather than at later fruit developmental stages (Chattha et al., 1999; Notodimedjo, 2000).

In summary, the largely equivocal assessment and description of fruit drop in mango render the comparison and interpretation of published data extremely difficult to draw general conclusions and providing horticultural recommendations. We therefore attempt to offer not only a new approach for assessing fruit drop data, based on a simple mathematical model, but also to newly characterize this process that occurs throughout the growing season from first flower to just before harvest. In particular, describing the fruit drop process, we are re-evaluating the appropriateness of existing terminologies in this context

and offering more precise benchmarks for onset and duration of each fruit drop stage. For a robust evaluation and validation of our model as well as the interpretation of the seasonal fruit drop continuum, fruit abscission was monitored over several years in varying mango production systems.

Material and Methods

Plant material and experimental sites.

The experiments were conducted over six consecutive growing seasons from 2007 to 2012 in the Tú Nang commune (lat. $20^{\circ}37'0'' \text{ N}$, long. $106^{\circ}4'60'' \text{ E}$) near the township Yên Châu, Province Sơn La, North Vietnam. This is a mountainous region with prevailing monsoon seasonality and 1200 mm of annual precipitation. Mango trees (*Mangifera indica* L.) of the cultivars Hôi and Tròn, ranging between 10 and 15 years of age, were used in several orchards for assessing fruit drop. The tree spacing in all orchards was $\approx 10 \times 10 \text{ m}$. Standard management practices such as, e.g., pruning and plant protection were conducted according to Huang (2004). Soils are classified as either Luvisol or Alisols (FAO, 2006).

Environmental parameters. Seasonal ambient air temperature and relative humidity were recorded within the center of each of six representative tree canopies in one orchard from 2006 to 2012 using microloggers (HOBO Pro v2; Onset, Bourne, MA). The logger outputs were recorded at 10-min intervals from 1 week before full bloom until midseason, covering the main fruit drop period, and average daily temperatures are shown in Table 1. There is little inter-seasonal variability and the 6-year daily mean was 30 and 17°C , 89% and 45% for maximum and minimum temperature, and relative humidity, respectively. In the same orchard, soil moisture was measured at weekly intervals from full bloom until midseason in 2008–09 with a profile probe

(PR2; Delta-t Devices Ltd., Cambridge, U.K.). The measurements were carried out at 10-cm increments from 10- and 40-cm soil depth 50 cm apart from the trunk of five irrigated and non-irrigated trees, respectively. The profile probe was connected to a handheld data-logging device (Moisture meter HH2; Delta-t Devices Ltd.).

Experimental design and treatments. Seasonal fruit drop was monitored in the same orchard where environmental parameters were monitored. Although the natural fruit drop of 'Hôi' was assessed in all years, fruit drop of both cultivars was also evaluated in response to irrigation and PGR applications in 2008 and 2009 (Table 2).

The irrigation experiment was conducted using 20 randomly selected trees per cultivar (Table 2). Ten trees were irrigated and 10 trees served as non-irrigated controls from ≈ 6 weeks before flowering until the end of the midseason drop. Trees were irrigated at 3-d intervals for 45 min with a nominal rate of $90 \text{ L} \cdot \text{h}^{-1}$. The irrigation system included microsprinklers (Gyro Net LR 120; Netafim, Tel Aviv, Israel) placed 30 cm to the tree trunks with water supplied from a rain-fed water tank.

For PGR applications, three trees in 2008 and six trees in 2009 for each cultivar, respectively, were randomly selected. Each of seven PGR treatments was applied to 10 panicles along one branch unit, respectively, on each experimental tree. The treated branches were randomly assigned within the block structure tree. The following PGR formulations were applied either alone or in combination according to manufacturers' specifications: 10 ppm CPPU (Sitofex 10 EC; AlzChem, Trostberg, Germany), 40 ppm GA₃ (ProGibb 40; Valent, Walnut Creek, CA), 40 ppm GA₄₊₇ (ProVide 10 SG; Valent), and 40 ppm NAA (Rhodofix; Syngenta, Basel, Switzerland). The treatments were 1) control (water); 2) CPPU; 3) CPPU + GA₃; 4) CPPU + GA₄₊₇; 5) NAA; 6) CPPU + GA₃ + NAA;

Table 1. Average daily maximum and minimum ambient temperatures and relative humidity, respectively, from 1 week before bloom to midseason in six consecutive growing seasons.²

Growing season	Temperature ($^{\circ}\text{C}$)		Relative humidity (%)	
	Maximum	Minimum	Maximum	Minimum
2007	28.1	15.0	88.9	43.2
2008	32.6	21.0	93.0	45.4
2009	31.3	17.3	90.4	38.4
2010	31.3	15.4	89.3	37.2
2011	25.2	16.8	85.9	58.3
2012	29.6	17.4	83.5	44.9

²Data were recorded in one orchard in the Tú Nang commune.

Table 2. Overview of experimental characteristics in each of six growing seasons.

Growing season	Full bloom	Cultivar	Treatment(s)	Trees/cv (no.)
2007	15 Feb.	Hôi, Tròn	—	10
2008	28 Mar.	Hôi, Tròn	Irrigation; PGR	20; 3
2009	6 Feb.	Hôi, Tròn	Irrigation; PGR	20; 6
2010	7 Feb.	Hôi	—	6
2011	7 Mar.	Hôi	—	6
2012	20 Feb.	Hôi	Cropping system	>8 ²

²In each of three orchards per cropping system. PGR = plant growth regulator.

and 7) CPPU + GA₄₊₇ + NAA. All treatments were sprayed at different fruit stages with the surfactant Ethalfix Pro (Syngenta) at a concentration of 5 ppm (Table 3). All applications were conducted at predawn to runoff using a pressure-compensated hand sprayer (Gloria; Typ 133, Witten, Germany). Spray drift was prevented by a plastic sheet surrounding the panicle at the time of application.

In addition, ‘Hôï’ monocropping and ‘Hôï’-maize intercropping were compared at three orchard sites, respectively, in 2012. Each site was used for at least 12 years in the current cropping system. At least eight trees were selected in each orchard, giving a total of 54 trees (Table 2).

Assessment of fruit drop. For counts of fruit retention, 10 (12 in 2012) healthy-appearing panicles were tagged at random for each tree or treatment shortly after full bloom. Counts started not later than 3 weeks after full bloom (greater than 90% of all panicles with less than 20% unbroken buds; approximately BBCH-scale 615) at weekly intervals. Fruit retention is expressed as the average fruit number per initially tagged panicles [fruit per panicle (FPP)]. In all years, fruit counts discontinued between 60 and 80 DAFB, ≈1 month before harvest, except in 2008 and 2011 when fruit retention was recorded until commercial harvest. According to the outlined inconsistent fruit drop definition, resulting from the use of “post-setting” as the denominator, fruit retention data are based on days after full bloom but not related to the BBCH-scale for reasons stated in the introduction.

Statistical analysis. Seasonal fruit drop was evaluated by analyzing counts of fruit retention per panicle at each assessment date. The timely patterns of average fruit retention were described with best fit regression functions using SigmaPlot 11.0 (Systat Software Inc., San Jose, CA). The mean data of each counting date were used for the regression analysis. The parameterized linear, polynomial, exponential decay, sigmoid, and logistic functions were compared for the best fit based on the adjusted correlation coefficient (r^2). Assumptions for the regression analysis, normality and variance homogeneity, were checked. The seasonal curves of FPP were best described with a four-parametric sigmoid function:

$$FPP(x) = y_0 + \frac{a}{1 + e^{-\frac{(x-x_0)}{b}}} \quad [1]$$

where x is the dependent variable DAFB. The parameter y_0 is diverging to positive infinity, marking the final fruit retention with assuming no changes until harvest. The sum y_0+a determines the upper limit of FPP(x) with divergence to negative infinity, matching the initial value of FPP. The parameter b is the steepness of the slope of the sigmoid function, whereas x_0 is its point of inflection, corresponding with the highest daily fruit losses in absolute terms. The constant e represents the Euler’s number. The FD(x) was calculated according to Zucconi et al. (1978):

$$FD(x) = 100 - \left(\frac{FPP_{(x+1)}}{FPP_{(x)}} * 100 \right) \quad [2]$$

FD(x) was plotted and the maximum value (FD_{max}) was determined from the graph. Moreover, a threshold was determined from data in the literature (Table 4), at which the midseason fruit drop is described to be ended [FD(x) midseason termination (FD_{mst})]. The appropriateness of x_0 , FD_{max}, and FD_{mst} for comparing sets of fruit drop data from the literature was tested.

The effects of cropping system, irrigation, and PGR applications on fruit retention were evaluated shortly after full bloom (BBCH-scale 615) and at the end of post-bloom (approximately BBCH-scale 701) and midseason drop (approximately BBCH-scale 703), respectively, by pairwise comparison of the means at a probability level of $P \leq 0.05$ (SAS 9.3; SAS Institute Inc., Cary, NC). However, after the first counting dates (greater than four), FPP did not follow normal distribution as a result of an increasingly high proportion of panicles bearing no fruit. Consequently, the positively skewed data, following a Poisson distribution, were evaluated with a generalized linear mixed model procedure (SAS Proc Glimmix) using a logarithmic link function and correction for the overdispersion of the errors (Bolker et al., 2009). Treatment means were estimated using the *lsmeans* statement in Proc Glimmix, which compensates for the unbalance in the data set (more observations in some treatments than in others). The model assumptions were checked by examining the residual plots.

Results

Assessment of fruit drop. The best approximation of the mean data of the two cultivars

in all six seasons and for both cultivars could be achieved by a sigmoid function with an r^2 of 0.85 (Fig. 1A). For a single season and cultivar, the data were best modeled with a sigmoid curve ($r^2 \geq 0.93$; Table 5). Time units other than DAFB have also been tested for increasing the accuracy of the fruit drop simulation overall growing seasons. The concepts evaluated were degree-days with base air temperatures 10, 13, and 15 °C (Issarakraisila and Considine, 1994; Whiley et al., 1988) and growth hours, the sum of all hours between 10, 13, or 15 °C and 36 °C. However, the resulting r^2 values were lower compared with those derived from using DAFB (data not shown). The slope of the simulated fruit drop curve shows a minimum at 23 DAFB where the sigmoid curve has its inflection point (Fig. 1B). FD(x), calculated from Eq. [2], showed a maximum at 31 DAFB (FD_{max}) and dropped below a threshold of 1.2% at 56 DAFB (FD_{mst}). The initial FPP (y_0+a) varied considerably, depending on cultivar and season, and was 5-fold greater in 2009 than in 2011 for ‘Hôï’, but this cultivar resulted not consistently in a higher initial FPP compared with ‘Tròn’ (Table 5). It is worth mentioning that there is no correlation between initial FPP and final fruit retention, because, e.g., a high y_0+a can lead to relatively high or low y_0 and vice versa. The duration between full bloom and the average occurrence of x_0 is 3 weeks in which ≈50% of the set fruit have dropped (Table 5). Subsequently, the drop intensity continuously to increase until FD_{max} is attained when on average only one-third of the fruit is still retained. The time period between full bloom and FD_{max} refers to the post-bloom drop stage that ends averagely at 31 DAFB. The following stage, the midseason drop, is characterized by a continuously decreasing fruit

Table 3. Fruit size-dependent time of spray application and concentration of each plant growth regulator (PGR).

PGR	Concn (ppm)	Fruit stage ^a	Fruit size (mm)	BBCH-scale	Time of application (DAFB)	
					2008	2009
CPPU	10	Pinhead	6	619	9 Apr. (12)	13 Feb. (7)
GA	40	Pea	11	NA	11 Apr. (14)	27 Feb. (9)
NAA	40	Marble	20	701	17 Apr. (20)	4 Mar. (26)

^aFruit stages as described by Malik and Singh (2003).

DAFB = days after full bloom; CPPU = N-(2-chloro-4-pyridyl)-N'-phenylurea; GA = gibberellin; NAA = 1-naphthaleneacetic acid; NA = not applicable.

Table 4. Literature citations with reference to the termination of post-bloom and midseason drop.

Publication	Days after full bloom	
	Post-bloom	Midseason
Thimmappaiah and Suman (1987)	29 ^a	59 ^a
Asif et al. (2002)	35 ^a	—
Bhuyan and Irabagon (1993)	21	—
Guzman-Estrada (1996)	—	39–64 ^{av}
Lam et al. (1985)	—	56 ^a
Núñez-Elisea and Davenport (1983)	—	54 ^a
Prakash and Ram (1984)	14	35
Singh and Arora (1965)	—	42
Singh et al. (2005)	74 ^a	89 ^a
Average	35	56

^aAuthors refer to “days after fruit set”; thus, to allow a comparison among various studies, 14 d were added to convert the time unit to days after full bloom according to the time duration cited by Notodimedjo (2000).

^{av}Range resulting from several cultivars being evaluated in that study.

drop intensity until FD_{mst} is reached at 56 DAFB (Table 5). There are slightly more fruit retained per panicle in 'Hôi' than in 'Tròn' but FPP is on average less than one. Thereafter, the average number of fruit per panicle is only moderately changing throughout the preharvest drop stage. For example, fruit retention of 'Hôi' decreased from 0.4 to 0.3 FPP and from 1.2 to 1.1 FPP in 2008 and 2011, respectively, from the end of midseason drop until harvest. The average $FD(x)$ over six consecutive seasons follows a single wave with the main fruit losses occurring between 20 and 40 DAFB

(Fig. 1B). In contrast, evaluating individual seasons indicates that fruit drop can occur in more than one wave (Fig. 2), except in 2011 and 2012 with only one wave. In most seasons, the last fruit drop wave has a smaller amplitude than the previous one.

Cropping system evaluation. The number of panicles per tree and the average number of fruit per panicle at each of the three fruit drop stages were not significantly different between the mango-maize intercropping system and the mango monocropping system (Table 6).

Irrigation. Fruit per panicle at the end of midseason drop was significantly increased in both cultivars by irrigation when compared with the control (Table 7). Interestingly, this effect was not seen in 2009 at the earlier stages, except for 'Hôi' at post-bloom. Fruit retention was considerably higher in 2009 compared with 2008. At harvest in 2008, irrigated trees retained 3-fold more fruit than non-irrigated trees in both cultivars. Despite these significant cropland differences, fruit length and fruit weight were similar in both treatments, resulting in on average 8- and 10-cm long and 180- and 230-g heavy fruit for 'Tròn' and 'Hôi', respectively. In general, soil moisture was 20% to 30% higher for irrigated trees compared with untreated controls. Moreover, soil moisture was higher in 2008 than in 2009 as a result of 196 mm precipitation in 2008 compared with only 1 mm in 2009.

PGR application. Fruit retention at the end of bloom, before PGR treatment, was significantly greater and more variable in 2009 than in 2008 (Table 8), indicating naturally, presumably environmentally induced differences. Nevertheless, all PGR applications resulted in greater numbers of fruit per panicle after the midseason drop when compared with the control treatment, regardless of cultivar and year (Table 8). This effect was already evident for the cultivar Tròn at the end of the post-bloom drop. Overall, the PGRs increased midseason fruit retention 2-fold in 2008, whereas it was 5- to 10-fold in 2009 compared with the controls. It is noteworthy that NAA and CPPU reduced most effectively the fruit drop, but the combination of both or either of these PGRs with GA did not lead to higher fruit retention. Similar to the irrigation experiment, the cultivar Hôi tended to have higher fruit retention than 'Tròn', particularly in 2009.

Fig. 1. (A) Average fruit retention per panicle (FPP) of 'Hôi' (closed symbols) and 'Tròn' (open symbols) in days after full bloom (DAFB). Each symbol refers to years between 2007 and 2012 and is based on actual fruit counts per panicle. Average fruit retention over that period is also modeled with a sigmoid function ($r^2 = 0.85$). y_0 is the final fruit retention, whereas y_0+a determines the upper limit of FPP. (B) Slope of the simulated fruit drop curve and the calculated daily rate of fruit drop $FD(x)$. Black arrows indicate x_0 , FD_{max} , and FD_{mst} , corresponding with the highest daily fruit losses in absolute terms, the highest $FD(x)$, and the cessation of midseason fruit drop, respectively.

Discussion

Fruit drop. The seasonal decrease of fruit retention in mango was described mathematically with a sigmoid function (Fig. 1) for two cultivars over several growing seasons. The sigmoidal shape is typical for many biological growth and developmental processes,

Table 5. Fruit per panicle (FPP) at days after full bloom (DAFB) for each growing season and cultivar.

Growing season and cultivar	r^{2z}	y_0+a^y FPP	x_0^x		FD_{max}^w		FD_{mst}^v	
			DAFB	FPP	DAFB	FPP	DAFB	FPP
2007 Hôi	0.98	10.9	23	5.6	49	1.7	95	0.3
2007 Tròn	0.95	11.0	27	5.4	43	1.0	76	0.1
2008 Hôi	0.99	8.8	23	4.9	29	1.8	45	0.4
2008 Tròn	1.00	10.4	22	5.2	31	1.3	52	0.2
2009 Hôi	1.00	28.5	16	14.9	30	3.5	59	0.5
2009 Tròn	0.99	18.7	22	9.5	30	2.9	51	0.5
2010 Hôi	0.99	9.1	19	5.0	22	3.1	35	1.1
2011 Hôi	1.00	5.7	31	3.3	35	2.4	50	1.2
2012 Hôi	0.93	18.9	21	10.2	29	3.5	49	0.8
Average		13.6	23	7.1	33	2.4	56	0.6

^zCorrelation coefficient of regression analysis (FPP * DAFB) using a sigmoid function.

^yInitial value of FPP at 0 DAFB.

^xHighest daily fruit loss in absolute terms.

^wMaximum value of $FD(x)$.

^vTermination of midseason fruit drop.

including mango fruit growth (Ram, 1983). Other mathematical functions, like for example the exponential decay, did not describe adequately the data scattering of fruitlet retention around bloom (Fig. 1A) as a result of the number of set fruit approximately equaling the number of abscised fruit until all

panicle have fully expanded (Mukherjee, 1953; Singh, 1954). Thereafter, fruit retention decreases with the steepest slope (x_0) at ≈ 3 weeks after full bloom (Fig. 1B), representing the highest daily fruit loss in absolute terms. Approximately 1 to 2 weeks later, the FD_{max} is highest, marking the end of the

post-bloom drop stage (Table 5) and corresponding well with average cited cessation dates of this drop stage (Table 4). By the end of the post-bloom drop, more than two-thirds of all fruit per panicle have dropped, presumably as a result of observed embryo degeneration and parthenocarpic fruit as one causal factor and indeed Singh and Arora (1965) found degenerated ovules (shrivelled seeds) in half of the abscised fruit. However, during midseason drop, they reported hardly any cases of embryo degeneration despite the occurrence of high fruit losses, which amounted to $\approx 20\%$ to 30% in the current study (Table 5). A physiological explanation of the midseason drop might be the shift from cell division during post-bloom drop to cell enlargement in midseason, which is accompanied by increased carbohydrate requirement of the fruit panicles. Defoliation experiments in citrus (Mehouachi et al., 1995; Ruiz et al., 2001) have indicated that the carbohydrate demand during early fruit growth is met by fruit photosynthesis and reserves in the fruiting wood, whereas midseason fruit growth depends increasingly on carbohydrates partitioned from leaves and therefore assimilate import through the fruit peduncle. Moreover, sucrose as the key translocation sugar in many plant species is predominantly transported to tissues with high auxin concentrations as shown, e.g., in ^{14}C labeling experiments (Dhanalakshmi et al., 2003). In mango, the accumulation of fruit auxins starts with the onset of the midseason drop and peaks ≈ 42 DAFB (Prakash and Ram, 1984), thus presumably acting as a strong sink signal for carbohydrate import into the fruit. Chattha et al. (1999) and Notodimedjo (2000) provide further support of this sink strength notion, showing that fruit losses are more effectively prevented in midseason than in the early season with exogenously applied synthetic auxins. This might be the result of augmenting the flow of endogenous auxin across the performed separation tissue layer of the pedicel beyond a critical fruit drop-inducing concentration (Sexton and Roberts, 1982). During the following pre-harvest drop stage (Fig. 1), the number of fruit per panicle changes little, likely because the carbohydrate demand by the fruit is matched by its supply and fewer environmental stresses occurring at that time of the growing season (Roemer et al., 2011).

In contrast to fruit retention data (Fig. 1A), $FD(x)$ results in one to three waves that occur between post-bloom and midseason drop (Figs. 1B and 2). This was described earlier for

Fig. 2. Daily rate of fruit drop in six consecutive growing seasons. Gray lines indicate the fruit drop waves by cultivar Hoi.

Table 6. Effect of mango monocropping and mango-maize intercropping systems on number of panicles per tree and number of fruits per panicle in 2012.

Treatment	Bloom (8 DAFB)	Post-bloom (32 DAFB)	Midseason (50 DAFB)
1. No. of panicles per tree			
Monocropping	494 a ^z	149 a	—
Intercropping	592 a	162 a	—
2. No. of fruits per panicle			
Monocropping	8.5 a	2.1 a	0.7 a
Intercropping	9.1 a	2.3 a	0.5 a

^zMeans followed by the same letter in each column do not differ significantly ($P \leq 0.05$). DAFB = days after full bloom.

Table 7. Effect of irrigation on fruit retention of mango for the growing seasons 2008 and 2009.

Treatment	Fruit per panicle						Harvest 2008
	Bloom		Post-bloom		Midseason		
	2008 (7 DAFB)	2009 (6 DAFB)	2008 (32 DAFB)	2009 (31 DAFB)	2008 (49 DAFB)	2009 (52 DAFB)	
Hôi control	9.1 c ^z	23.7 a	0.9 c	3.8 b	0.3 b	0.4 b	0.3 c
Irrigation	10.5 b	22.8 a	3.2 a	4.6 a	1.7 a	2.8 a	0.8 a
Tròn control	9.8 bc	19.2 b	0.8 c	3.1 b	0.1 c	0.3 b	0.1 d
Irrigation	11.4 a	18.2 b	2.5 b	5.0 b	1.3 a	2.4 a	0.7 b

^zMeans followed by the same letter in each column do not differ significantly ($P \leq 0.05$). DAFB = days after full bloom.

Table 8. Effect of plant growth regulator application for the growing seasons 2008 and 2009.

Treatment	Fruit per panicle						Harvest 2008
	Bloom		Post-bloom		Midseason		
	2008 (4 DAFB)	2009 (6 DAFB)	2008 (32 DAFB)	2009 (31 DAFB)	2008 (49 DAFB)	2009 (52 DAFB)	
1. Hôi							
Control	12.3 a ^z	16.0 ab	4.1 a	3.7 c	1.4 d	0.4 d	0.2 c
CPPU	12.6 a	15.1 bc	4.1 a	5.9 a	3.1 b	2.6 a	0.6 b
CPPU + GA ₃	12.4 a	15.2 bc	4.7 a	5.3 b	2.6 c	2.5 a	0.3 c
CPPU + GA ₄₊₇	11.8 a	17.2 a	3.6 a	3.7 c	2.4 c	0.9 c	0.1 c
NAA	11.5 a	14.0 c	4.0 a	3.0 c	3.6 a	2.3 a	0.8 a
NAA + CPPU + GA ₃	12.6 a	14.6 bc	3.3 a	5.9 a	2.6 c	2.4 a	0.6 b
NAA + CPPU + GA ₄₊₇	13.0 a	16.5 ab	4.0 a	5.1 b	2.4 c	1.3 b	0.3 c
2. Tròn							
Control	12.3 a	20.1 a	2.6 c	1.6 d	1.6 d	0.1 d	0.3 bc
CPPU	12.2 a	21.1 a	4.1 a	4.8 a	3.5 ab	1.6 a	0.3 c
CPPU + GA ₃	12.1 a	15.4 ac	3.8 a	4.5 a	2.6 c	0.9 b	0.3 c
CPPU + GA ₄₊₇	12.3 a	17.8 ab	3.3 b	2.5 c	2.7 c	0.5 c	0.4 bc
NAA	11.5 a	19.2 a	4.0 a	3.7 b	3.7 a	1.5 a	0.7 a
NAA + CPPU + GA ₃	12.2 a	14.9 bc	3.7 ab	4.0 b	3.0 bc	1.4 a	0.6 ab
NAA + CPPU + GA ₄₊₇	12.3 a	15.1 c	3.8 ab	2.7 c	3.0 bc	0.3 cd	0.5 bc

^zMeans followed by the same letter in each column and for each variety do not differ significantly ($P \leq 0.05$, $n = 30$ in 2008; $n = 60$ in 2009).

DAFB = days after full bloom; CPPU = N-(2-chloro-4-pyridyl)-N'-phenylurea; GA = gibberellin; NAA = 1-naphthaleneacetic acid.

Table 9. Correlation coefficients between fruit retention data at the end of post-bloom or midseason drop with harvest.

Publication	Cultivar	Treatment	Sum	Post-bloom		Midseason	
				DAFB	r^2	DAFB	r^2
Thimmappaiah and Suman (1987)	13	1	13	29 ^z	0.43^y	59	0.26
Notodimedjo (2000)	1	7	7	35	0.69	56	0.59
Stino et al. (2011)	6	5	30	29	0.15		
Current study (PGR)	2	7	14	32	0.00	49	0.42
Current study (irrigation)	2	2	4	32	0.95	49	0.98
Guzman-Estrada (1996)	5	1	5	39	0.03	64	0.33
Bhuyan and Irabagon (1993)	1	12	12	21	0.16	56	0.83

^zAuthors refer to "days after fruit set"; thus, to allow a comparison among various studies, 14 d were added to convert the time unit to DAFB according to the time duration cited by Notodimedjo (2000).

^yBold coefficients indicate a moderate or strong correlation.

DAFB = days after full bloom; PGR = plant growth regulator.

mango as well as for other fruit trees, including litchi and orange (Guzman-Estrada, 1996; Prakash and Ram, 1984; Yuan and Huang, 1988; Zucconi et al., 1978). Some polyembryonic mango cultivars, like for example 'Hôi' and 'Tròn', are more cold-sensitive than monoembryonic cultivars (Elsheery et al., 2007; Sukhivilul et al., 2000). Consequently, cold-adapted mango cultivars are better suited for cultivation in the subtropical climate of northern Vietnam, where ambient temperatures below 15 °C with "zero growth" in mango (Whiley et al., 1988) occur frequently. However, there was no correlation between FD(x) and high/low ambient temperatures and/or low relative humidity as was proposed as a cause for premature fruit drop in tree crops (Roemer et al., 2011; Yuan and Huang, 1988; Zucconi et al., 1978).

It has been reported that the fruit set at the end of the post-bloom drop is already pre-determining the final yield at harvest (Thimmappaiah and Suman, 1987) and evaluating the data of Notodimedjo (2000) allows the same conclusion. This notion, however, is not in agreement with the current findings and other results in the literature (Guzman-Estrada, 1996; Stino et al., 2011) (Table 9). In contrast, fruit retention at the end of the midseason fruit drop stage was in good agreement with that at harvest in 2008 (Table 9) and this is confirmed by other studies (Bhuyan and Irabagon, 1993; Guzman-Estrada, 1996; Notodimedjo, 2000).

Subsequently, the midseason fruit retention data are useful for yield estimates and evaluating the effect of fruit drop prevention treatments on final yield.

Climatic factors. Early fruit development was characterized by daily fluctuations of cold nights and hot daytime temperatures (Table 1) as well as strong, hot, and dry winds as described in detail by Roemer et al. (2011). According to earlier findings, wind velocity is unlikely to provide sufficient force necessary for the detachment of healthy fruit and therefore may only force unhealthy fruit with loosely adhering junctions to drop (Singh et al., 2005; Singh and Arora, 1965). However, dry conditions seem to be detrimental to orchard productivity of mango because irrigation increased fruit retention significantly. The average yield of $\approx 1 \text{ t} \cdot \text{ha}^{-1}$ is, however, still much lower compared with the $8 \text{ t} \cdot \text{ha}^{-1}$ achieved on average internationally (FAOSTAT, 2012) as well as in the key Vietnamese mango production areas of the Mekong Delta and the southeast (IFPRI, 2002).

Cropping system. The review of Singh et al. (2005) describes that intercropping can induce increased fruit drop in mango. This is not in agreement with the current study, in which a mango-maize intercropping system had no detrimental effects on the number of panicles per tree and number of fruit per

panicle when compared with monocropping systems (Table 6). This may be explained by farmers paying more attention to tree management practices in intercropping systems, because of more frequent field visits and thus observation time (Roberts-Nkrumah, 2000).

Irrigation. The positive effect of irrigation on fruit retention (Table 7) is in good agreement with other irrigation studies of mango (Larson et al., 1989; Spreer et al., 2009). In the current study, irrigation started before bloom because earlier studies have shown greater flower abundance and fruit set on irrigated than on non-irrigated trees (González et al., 2004). Care was taken that water was not applied too early in the dry season because it was reported that a greater amount of vegetative buds rather than flower buds are produced (Coelho and Borges, 2004). Indeed, the number of fruit per panicle around bloom in 2008 was only approximately half of that in 2009, presumably the result of more precipitation and 3 weeks earlier irrigation commencement in 2008 than in 2009. Alternatively, the yearly fruit retention differences might also be explained by the formation of more vegetative flushes in 1 year and the irregular bearing habit of mango (Davenport, 2006; Huong, 2010). The differences between irrigated and non-irrigated trees were much higher after midseason drop than post-bloom drop in agreement with the concept that

drought causes reduced rates of leaf net photosynthesis and thus carbon supply limitations to the developing fruit particularly in midseason (Damour et al., 2009). In general, irrigation is an effective method for reducing fruit drop. However, the construction of an irrigation system proves to be difficult in the mountainous regions of Són La because most orchards are far away from water sources and in most cases there is little infrastructure that would allow long-distance or uphill transport of water (personal communication, participants of the Tú Nang Mango Grower Workshop 2012).

PGR. The applications of PGRs was also a successful strategy for increasing fruit retention (Table 8) and resulted in similar or even higher fruit retention values than the irrigation treatment. The spray application of CPPU between 7 and 12 DAFB was earlier than the use of all other PGRs and the enhancing effect on fruit retention was already noticeable during the post-bloom drop. Because Burondkar et al. (2009) showed a positive effect of CPPU on leaf chlorophyll content in mango, it can be deduced that leaf net photosynthesis and subsequently the amount of carbohydrates available in support of fruit growth were also increased and this in turn might have prevented fruit drop. CPPU, like their natural analogs, is known for promoting cell division and is therefore used for increasing fruit growth, e.g., in kiwi production (Iwahori et al., 1988; Mok and Mok, 2001). Indeed, the harvest in 2008 showed a 20% increased fruit size for CPPU-treated mango when compared with the control fruits (data not shown). In addition, cytokinins promote vascular tissue differentiation, therefore increasing the transport capacity of resources into the fruit, which might have strengthened CPPU-treated fruits and thus reduced fruit drop. At the end of the midseason drop, all PGR treatments had significantly higher fruit retention compared with the control. Nevertheless, CPPU and NAA resulted consistently in the highest midseason fruit retention for both cultivars, but the NAA treatment had the greatest number of fruit per panicle at harvest compared with all other PGR treatments (Table 8). Based on these findings, both substances can be recommended to growers as an effective measure for fruit drop prevention.

Conclusion

The presented mathematical model for the seasonal fruit drop pattern of mango allowed the partitioning into three distinct stages: the post-bloom, the midseason, and the preharvest drop, respectively. Each stage was characterized by specific parameters that explained the variability in fruit drop, induced by cultivar, season, and treatment, and permits the evaluation of the 1) natural variation before the treatment effect during post-bloom drop; 2) treatment efficacy during midseason drop; and 3) yield forecasting at the beginning of the preharvest stage. Moreover, the model proposes a systematic and standardized approach for distinguishing between the drop stages, thus making the comparison between published data more precise and consistent. The

results of the experiments lead to useful and applicable general recommendations for mango growers to alleviate fruit drop, particularly under the prevailing growing conditions in northern Vietnam: 1) mango–maize intercropping systems are not disadvantageous over mango monocropping; and 2) pre-bloom irrigation when a required infrastructure is available or, alternatively, spray applications of NAA.

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