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The impact of downy mildew on high-value cucurbit crops in the US: an econometric analysis

Ramu Govindasamy[1]*, Surendran Arumugam[2], Mary Hausbeck[3], Andrew Wyenandt[4], and James E Simon[5]

[1]Department of Agricultural, Food and Resource Economics, Rutgers-The State University of New Jersey, New Brunswick, NJ 08901-8520
[2]Department of Agricultural Economics, Centre for Agricultural and Rural Development Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Department of Plant, Soil and Microbial Sciences, Michigan State University, Plant Biology Laboratories, East Lansing, MI 48824
[4]Rutgers Agricultural Research and Extension Center, Rutgers New Jersey Agricultural Experiment Station, Bridgeton, NJ 08302-5919
[5]Rutgers University, Department of Plant Biology, Center for Agricultural Food Ecosystems (RUCAFE), New Brunswick, New Jersey 08901

*Corresponding author: govind@sebs.rutgers.edu

Abstract This paper describes the impact of cucurbit downy mildew (CDM) on high-value crops in the United States. The estimated logit model indicates that farmers who use plastic mulch, consider curcubits their primary crop, and utilize agricultural extension services are likely to minimize yield losses due to CDM, and farmers over 65 who use raised beds and overhead irrigation are more likely to incur higher losses. Our findings are helpful in understanding the outbreak of CDM and the on-farm strategies farmers use to mitigate the disease.

Keywords Cucurbit downy mildew (CDM), outbreak, high-value crops, farmer survey, logit model framework

JEL codes Q1, Q10, Q12

The cucurbit downy pathogen infects diverse cucurbit genera (Lebeda and Urban 2007; Palti and Cohen 1980; Savory et al. 2011). The pathogen is disseminated via windblown sporangia, and it may be transported up to 600 miles. An outbreak of the cucurbit downy mildew (CDM) disease, induced by *Pseudoperonospora cubensis*, may spread rapidly in a short period under favourable environmental conditions and present a threat to cucurbit crops and growers over a vast geographical region (Keinath 2015). Over 70 nations have reported CDM; it causes substantial yield reductions in the US, Europe, China, and Israel (Thomas 1996).

In 2004, the resurgence of CDM in the eastern US devasted production in North Carolina, Virginia, Delaware, Maryland, New Jersey, and other states, and it reduced yield by 40%. In the case of cucumber, genetic resistance was not adequate in mitigating the re-emerged pathogen (Lebeda and Widrlechner 2003); and losses that year were assessed at USD 20 million (INR 150 crore) (Holmes et al. 2006).

Since 2005, outbreaks of CDM have been reported every year in the state of Michigan, the largest supplier of pickling cucumber in the US, and the annual cost of additional fungicide applications has been estimated to exceed USD 6 million (INR 45 crore). The disease has negatively impacted cucumber production in Michigan and other regions and threatened its long-term viability (Savory et al. 2011).

Currently, fungicides are used intensively to control outbreaks of CDM in the US, but season-long fungicide programmes are expensive, and pathogens are likely to develop resistance to systemic fungicides that were once highly effective (Savory et al. 2011). In 2004, growers observed the *P. cubensis* population to be resistant to the commonly used fungicides, mefenoxam and azoxystrobin (Holmes et al. 2015). Since then, new fungicides have been registered and used for CDM control; yet, the pathogen has developed resistance to all but a few (Call et al. 2013). Growers can use disease forecasting systems (CDM ipmPIPE) (Holmes et al. 2015) and early warning monitoring systems (Bello et al. 2021) to time the application of preventative fungicides, especially in northern growing regions where the pathogen does not overwinter.

Host resistance is considered optimal to limit disease. But the CDM pathogen that re-emerged in 2004 overcame the genetic resistance once inherent in commercial cucumber cultivars. The use of fungicide has been observed to be less effective in reducing disease than genetic resistance (Call et al. 2013), which has successfully been bred into other high-value crops such as sweet basil (*Ocimum basilicum*), susceptible to a different downy mildew pathogen (*Peronospora belbahrii*) (Pyne et al. 2017; Pyne et al. 2018). Breeding efforts to develop similarly disease-resistant pickling cucumber have met mixed success; while these commercially available cultivars are more resistant than the CDM-susceptible cultivars, fungicides are still required for optimum yield (Pyne et al. 2017; Pyne et al. 2018).

Integrated research approaches and integrated pest management (IPM) strategies should consider the perceptions and preferences of farmers and the socio-economic constraints of CDM control options. As such, we conducted a survey to assess the strategies farmers used to overcome or mitigate the impact of downy mildew on high-value cucurbit crops.

Methodology

A survey of cucurbit growers was conducted—in the states of Iowa, Michigan, New York, and Ohio, in the US—to gather information on the field production of high-value cucurbit crops: pickling cucumber, slicing cucumber, squash, pumpkin, cantaloupe, and watermelon. The primary objective of the survey, conducted in 2017, was to document the extent of damage caused by CDM in cucurbits and the control measures used by producers to mitigate the damage. The survey assessed the baseline information on crop production, participation in agricultural extension activities, and farmer demographics.

The person in charge of farming activity was identified and interviewed after they consented. The consent form developed by the researchers was approved, along with the questionnaire, by the Offices of Research Protections at Michigan State University and Rutgers, The State University of New Jersey.

Data limitation

Some participants did not keep records, and it is possible that the data collected may not be accurate in certain cases; in such cases we asked the cucurbit growers probing questions to get answers that were as accurate as possible. Asking for details such as land size in acreage and then in square metre also contributed to the difficulty in acquiring accurate data. Some farmers were reluctant to share information on income and income sources, and they did not offer the exact information. Some questions were repetitive—the same information twice, for two different periods—and hence caused problems in obtaining quality data.

Logit model framework

We developed the logit model framework to estimate the factors that influence an outbreak of CDM. In addition to considering farmers' choices, production practices, and socio-economic constraints, the proposed logit model uses a random utility method (Arumugam et al. 2020; Arumugam et al. 2019; Govindasamy et al. 2018; Govindasamy et al. 2018). We used the maximum likelihood estimation (MLE) procedure as it delivers reliable parameter estimates that are asymptotically effective (Gujarati 1992; Pindyck and Rubinfeld 1991).

We explored the relationship between the level of outbreak—either low (less than 20%) or high (more than 20%)—and farmers' characteristics, choices, production practices, and socio-economic constraints by modelling the sign variable Z_i for the i^{th} farmer as a function of their choices and other independent variables:

$$Z_i = \boldsymbol{\beta}\mathbf{X}_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik} + \nu_i, \quad i = 1, 2, \ldots, n \tag{1}$$

where x_{ij} represents the j^{th} characteristics, choices, production practices, and socio-economic constraints of the i^{th} farmer;

$\boldsymbol{\beta} = (\beta_0, \beta_1, ¼, \beta_k)$ is the parameter to be estimated; and

n_i is the random error or disturbance term associated with the i^{th} farmer.

Under the logistic distributional assumption for the random term, the probability P_i is expressed as:

$$P_i = F(Z_i) = F(\beta_0 + \sum_{j=1}^{k} \beta_j x_{ij}) = F(\boldsymbol{\beta}\mathbf{X}_i) = \frac{1}{1+\exp(-\boldsymbol{\beta}\mathbf{X}_i)} \tag{2}$$

The β-coefficients of Equation 2 do not directly denote the marginal effects of the explanatory variable on the probability of Pi. In the case of a continuous explanatory variable, the marginal effect of xj on the probability Pi is given by

$$\partial P_i / \partial x_{ij} = \left[\beta_j \exp(-\boldsymbol{\beta}\mathbf{X}_i)\right] / \left[1+\exp(-\boldsymbol{\beta}\mathbf{X}_i)\right]^2 \tag{3}$$

However, if the explanatory variable is qualitative or discrete, $\partial P_i / \partial x_{ij}$ does not exist; the marginal effect is attained by assessing Pi at the alternative values of xij. For example, in the case of a binary explanatory variable, where x_{ij} takes the value of 1 or 0, the marginal effect is denoted as

$$\partial P_i / \partial x_{ij} = P(x_{ij} = 1) - P(x_{ij} = 0) \tag{4}$$

To capture the relationship between the level of CDM and crop production practices, producer characteristics, and socio-economic constraints, we specified the empirical model

CDM reduces yield by more than 20% =

β_0 + β_1 male + β_2 education ug + β_3 business experience + β_4 primary income + β_5 age over 65 + β_6 above 1000 acre + β_7 raised beds + β_8 direct seeded + β_9 plastic mulch + β_{10} over head irrigation + β_{11} primary crop + β_{12} disease problem + β_{13} dm more infestation + β_{14} cdm resident varieties + β_{15} crop insurance + β_{16} agrl. extension service —— —— $!_i$ (5)

The framework of the logit model and the computed results are based on STATA; the logit model response and variables are presented in Table 1.

Among the explanatory variables, business experience is a discrete variable; the others are dualistic binary (dummy) variables. The discrete variables are described in average units; the dummy variables are expressed as a percentage. Nearly 39% of the farmers reported that CDM damaged their crop severely, or they lost more than 20% of their yield; the remaining 61% reported that the damage was minimal, or they lost less than 20% of their yield.

Results and discussion

Demographics

In total, there were 98 respondents from four states: Iowa, Michigan, New York, and Ohio; 92 from Michigan (93.88%), 3 from New York (3.06%), 2 from Ohio (2.04%), and 1 from Iowa (1.02%) (Table 2).

Land ownership and use

We used the information given by the respondents to determine the sizes of land parcels and group these by acreage (Table 2). Of the 98 respondents, 32 (32.65%) owned more than 1,001 acres and 22 (22.45%) less than 50 acres; and 11 each (11.22%) owned farms of 50–100 acres and 501–1,000 acres. Ten respondents (10.22%) owned between 251–500 acres and 7 between 105–250 acres; 5 of the 98 respondents (5.10%) did not respond to this question.

Primary income from farming

Farming was the primary source of income of 55 respondents (61.10%); 35 respondents, or 38.89% of the total, indicated that farming was not their primary source of income. Eight participants did not answer this question. Farming experience averaged 27.73 years.

Crop production per season

Only 40 of 98 respondents answered the question on crop production: 13 respondents (32.5%) stated that they cultivated 3–5 crops per season, 9 respondents (22.5%) cultivated 1–2 crops, 8 respondents (20%) cultivated 6–10 crops, and 7 respondents (17.50%) cultivated 11–19 crops. Only 3 respondents (7.5%)

Table 1 Variables used to predict the impact of downy mildew on cucurbit crops

	Variable	Description	Mean / %
		Dependent variables	
	More than 20%	1 if the yield loss due to CDM is more than 20% of cucurbits, 0 otherwise	39%
		Independent variables	
1.	Male	1 if the farmer is male, 0 otherwise	89%
2.	Education UG	1 if the farmer studied up to the undergraduate level, 0 otherwise	25%
3.	Business experience	Number of years of farming experience	29.16
4.	Primary income	1 if the farmer receives their primary income through farming, 0 otherwise	65%
5.	Age over 65	1 if the farmer's age is over 65 years, 0 otherwise	12%
6.	Above 1,000 acres	1 if the farmer holds more than 1000 acres, 0 otherwise	37%
7.	Raised beds	1 if the farmer uses raised plant beds to grow cucurbits, 0 otherwise	26%
8.	Direct seeded method	1 if the farmer follows the direct-seeded method to grow cucurbits, 0 otherwise	61%
9.	Plastic mulch	1 if the farmer uses plastic mulch to grow cucurbits, 0 otherwise	16%
10.	Overhead irrigation	1 if the farmer uses overhead irrigation to grow cucurbits, 0 otherwise	40%
11.	Primary crop	1 if the farmer considers cucurbits as the primary crop, 0 otherwise	68%
12.	Disease problem	1 if the farmer considers disease in general as a major issue among the other obstacles, 0 otherwise	19%
13.	CDM outbreak	1 if the farmer is experiencing more CDM now compared to 5 years ago, 0 otherwise	33%
14.	CDM-resistant cultivars	1 if the farmer uses CDM-resistant cultivars, 0 otherwise	53%
15.	Crop insurance	1 if the farmer accesses a crop insurance service, 0 otherwise	70%
16.	Extension education	1 if the farmer received disease management and CDM mitigation training through the agricultural extension service, 0 otherwise	47%

Source Survey data, 2017

produced 20–30 crops per season. On average, 6.99 crops were produced per season.

The impact of cucurbit downy mildew (CDM)

To control CDM, growers use resistant cultivars and implement fungicide programmes; together, these form an effective IPM approach (Table 3). The primary crops include the most commonly grown and bestselling crops: pickling cucumber, squash, and pumpkins.

Thirty-seven respondents stated that they frequently grew pickling cucumber; 32 (86.49%) reported it as their primary crop. Squash was cultivated by 37 respondents, and 18 (48.65%) reported it to be their primary crop; whereas 34 respondents (91.89%) grew pumpkins and 21 (56.75%) reported it as the primary crop.

Similarly, slicing cucumber had 19 respondents, and 9 (47.37%) considered it to be their primary crop; and cantaloupe had 11 respondents, and 4 (36.36%) considered it to be their primary crop. Among the least-mentioned primary crops, watermelon had 10 respondents, of which 2 (20%) considered it to be their primary crop.

All these crops were affected by CDM, according to the respondents. Pickling cucumber was the worst affected; 35 respondents (94.59% of those who grew the crop) reported an outbreak. This was followed by cantaloupe with 7 responses (63.64%), sliced cucumber with 11 responses (57.89%), pumpkin with 19 responses (55.88%), squash with 17 responses (45.95%), and watermelon with 4 responses (40%).

Table 2 Farm business details of growers who completed the survey

	Particulars	Frequency	Percent (%)
1.	Michigan	92	93.88%
2.	New York	3	3.06%
3.	Ohio	2	2.04%
4.	Iowa	1	1.02%
	Total	98	100.00%
I.	Land ownership and use		
1.	Less than 50	22	22.45%
2.	50–100	11	11.22%
3.	105–250	7	7.14%
4.	251–500	10	10.22%
5.	501–1000	11	11.22%
6.	Above 1001	32	32.65%
7.	Not reported	5	5.10%
	Total	98	100.00%
	Primary income from farming		
1	Yes	55	61.11%
2	No	35	38.89%
	Total	90	100.00%
	Number of crops / seasons		
1.	1–2	9	22.50%
2.	3–5	13	32.50%
3.	6–10	8	20.00%
4.	11–19	7	17.50%
5.	20–30	3	7.50%
	Total	40	100.00%
	Particulars	Average	
1.	Average years of farming	27.73	-
2.	Average number of crops produced	6.99	-

Source Survey data, 2017

A fungicide programme was the most common method used to overcome CDM. All the 37 respondents who cultivated pickling cucumber reported using a fungicide programme while 18 respondents (48.65%) reported using CDM-resistant varieties.

Of the farmers who cultivated slicing cucumber, 15 (78.95%) reported using a fungicide programme, and 11 (57.89%) used resistant cultivars. Of those who grew watermelon, 7 (70%) used a fungicide programme and 4 (40%) used resistant cultivars.

Among squash cultivators, 24 (64.86%) used a fungicide programme and 16 (43.24%) used resistant cultivars. Among the respondents who grew cantaloupe, 9 (81.82%) used a fungicide programme and 6 (54.55%) used resistant cultivars.

Lastly, among pumpkin cultivators, 24 (70.59%) used a fungicide programme and 16 (47.06%) used resistant cultivars.

It is important to note that except for cucumbers, no varieties of cucurbits are resistant to CDM. This stresses the importance of grower education and training to control CDM.

Empirical results for logit model estimates

The logit model analyses the characteristics of farmers who lost more than 20% of their yield to CDM. In the total sample, the precise likelihood outcome of the response variable is 85.96% (Table 4). The χ^2 statistics rejected the null hypothesis, McFadden

Table 3 Crop preference, CDM outbreaks, and the mitigation strategies of farmers

	Crop		Primary crop	CDM outbreaks	CDM mitigation strategies*		Total respondents
					Resistant varieties	Fungicide programme	
1.	Pickling cucumber	Frequency	32	35	18	37	37
		%	86.49	94.59	48.65	100.00	100.00
2.	Squash	Frequency	18	17	16	24	37
		%	48.65	45.95	43.24	64.86	100.00
2.	Pumpkin	Frequency	21	19	16	24	34
		%	67.76	55.88	47.06	70.59	100.00
3.	Slicing cucumber	Frequency	9	11	11	15	19
		%	47.37	57.89	57.89	78.95	100.00
4.	Cantaloupe	Frequency	4	7	6	9	11
		%	36.36	63.64	54.55	81.81	100.00
5.	Watermelon	Frequency	2	4	4	7	10
		%	20.00	40.00	40.00	70.00	100.00

Source Survey data, 2017

Table 4 Logit model predictive accuracy

Classified	True		Total
	D	~D	
+	26 (45.61%)	5 (8.77%)	31 (54.39%)
–	3 (11.54%)	23 (88.46%)	26 (45.61%)
Total	29 (50.88%)	28 (49.12%)	57 (100.00%)

No. of observations = 57 successful predication rates: 85.96%; pseudo R^2: 0.5387; Prob > chi^2 = 0.0003

pseudo-R-squared is 0.5387, and the overall model significance is 0.0003.

The estimated logit model result indicates that farmers who use plastic mulch, cultivate cucurbits as their primary crop, and access agricultural extension services are less likely than others to lose more than 20% of their yield (Table 5). However, farmers older than 65 years and who use raised beds and overhead irrigation systems are more likely than others to incur a high yield loss.

Our results show that those who use plastic mulch are less likely to incur a high yield loss due to CDM outbreaks compared to those who use other mulches. Polyethylene / plastic mulches are commonly used for weed control (Grundy and Bond 2007; Ristaino and Thomas 1997), solar soil disinfection (Katan and DeVay 1991), and to safeguard crops from diseases spread by insect pests (Antignus 2007).

Also, compared to those who grew cucurbits as a secondary crop, those who consider cucurbits their primary crop are less likely to incur high yield losses due to a CDM outbreak. Those who grow cucurbits as a primary crop are often more knowledgeable about CDM mitigation measures and, as a result, can control the disease better compared to those who cultivate cucurbits as a secondary crop.

Further, the farmers who avail of agricultural extension services are less likely to incur a high yield loss due to CDM compared to those who do not utilize extension services as they are more likely to have access to disease management training. Also, one of the most significant obstacles to crop production according to the participants was identifying disease development. This survey shows that the use of agricultural extension services is enhancing the farmers' knowledge and skills in controlling CDM.

Likewise, those who use overhead irrigation are more like to incur a high yield loss due to CDM compared to those who use other forms of irrigation (such as drip irrigation). The use of overhead irrigation promotes

Table 5 Logit model estimates of cucurbit downy mildew

	Particulars	Variables	Co-efficient	Std. Err.	Marginal effect
1.	Socio-economics characteristics	Male	2.6715	2.4118	-
		Education UG	1.0718	1.4238	-
		Business experience	–0.0498	0.0347	-
		Primary income	0.1337	1.6977	-
		Aged over 65	4.6298**	2.1623	0.7086
2.	Crop production practices	Above 1000 acre	–0.4285	1.2476	-
		Raised beds	8.9094***	3.5137	0.9403
		Direct seeded	2.0196	1.4462	-
		Plastic mulch	–4.9506**	2.5284	–0.5721
		Overhead irrigation	6.3445***	2.2055	0.9186
		Primary crop	–3.5572**	1.7543	–0.7074
3.	CDM outbreak and mitigation	Disease problem	0.5329	1.2423	-
		CDM increased outbreak	–0.1970	1.0634	-
		Resident cultivars	–0.4387	0.9580	-
4.	Other social relations	Crop insurance	–0.3666	1.1268	-
		Agricultural extension service	–2.3381*	1.3285	–0.5015

(*Note* *, **, *** significant at the 10%, 5%, and 1% levels, respectively).

long periods of leaf wetness and increases relative humidity in the canopy, creating conditions favourable for CDM development (Hansen 2009).

Further, those who are above 65 years of age are more likely to incur high yield losses due to CDM compared to younger farmers; about 12% of the respondents belonged to this category. Although older farmers may have more experience in crop production, they may not be aware of the most effective methods (e.g., resistant cultivars, effective fungicide programmes) to limit CDM. Younger farmers may be able to access the latest information regarding the control of CDM through various sources including social media and networking.

Conclusion

This paper documents the practices used by farmers to overcome the impacts of downy mildew on cucurbit crops (pickling cucumber, squash, pumpkin, slicing cucumber, cantaloupe, and watermelon). In total, 98 respondents participated in a field-level survey. According to the survey, all the included crops were affected by CDM to some degree. Pickling cucumber had the largest CDM outbreaks followed by cantaloupe, sliced cucumber, pumpkin, squash, and watermelon.

The estimated logit model result suggests that farmers who belong to one of the following three categories are less likely to incur a high yield loss due to CDM: i) those who used plastic mulch to grow cucurbits, ii) those who considered cucurbits their primary crop, and iii) farmers who availed agricultural extension services. Generally, growers who process cucurbits in Michigan do not use plastic mulch to grow cucurbits. Also, growers who use black plastic mulch mostly use drip irrigation. Farmers who use raised beds to grow cucurbits, those who use overhead irrigation, and farmers above the age of 65 years are more likely to incur high yield loss due to CDM.

There are a few growers in Michigan who use raised beds without plastic mulch and drip irrigation. However, some retailers and fresh market growers use raised beds to grow other crops. Hence, extension-based outreach should include information on CDM-resistant cultivars, effective fungicide programmes, and the need to avoid overhead irrigation to limit CDM outbreaks. This information needs to be disseminated using various methods.

In this survey, we identified that the most common method for limiting CDM was using a fungicide programme along with resistant cultivars. Extension-based outreach and IPM should be explored to further reach out to "older" farmers to help improve CDM control. The information from this survey has the potential to impact future endeavours to help mitigate CDM with an emphasis on helping the producer employ the most current resources available.

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