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SOURCE TESTING OF PARTICULATE MATTER EMISSIONS FROM COTTON HARVESTERS – SYSTEM DESIGN

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Abstract

Recent air quality legislation has placed increased pressure on agricultural producers in several states across the US. In particular, California removed the exemption for agricultural sources from air quality permitting in 2003. Through the use of inaccurate particulate matter emission factors, agricultural operations have been targeted as significant sources of particulate matter emissions. The emission factors used by regulators in California were developed using techniques with high levels of uncertainty. The objective of this manuscript is to present a novel approach to measuring source emission concentrations from cotton harvesting operations. The proposed sampler design would collect all of the harvested seed cotton, trash, and conveying air at the exit of the conveying ducts used to transport the harvested material to the basket. The air and entrained particulate matter would be separated from the seed cotton and large trash inside a dropper box where isokinetic concentration measurements would be taken at a point just before the air and entrained particulate matter is exhausted to the outside. Subsequent particle size distribution analyses of the particulate matter collected from the isokinetic samples would be used to determine the corresponding PM_{10}, $PM_{2.5}$, and $PM_{10\text{-}2.5}$ source emission concentrations. Finally, particulate matter emission factors would be calculated (for each size fraction indicator i.e. $PM_{2.5}$, PM_{10}, or $PM_{10\text{-}2.5}$) on both a lbs/acre and lbs/bale harvested basis. It is expected that the techniques discussed in this manuscript would yield more accurate science based emission factors than the emission factors currently in use.

Introduction

The USEPA delegates the power to enforce air quality regulations to state air pollution regulatory agencies (SAPRAs). As a result, the SAPRA in each state is responsible for ensuring that the air quality within the state is in compliance with federal air quality standards. Each year, states are required to submit a state implementation plan (SIP) detailing the actions that the state will take to ensure that the air quality within the state is in compliance with federal air quality standards. Some states have areas in which the air quality is not in compliance with federal standards (non-attainment areas). These states are required to include in their SIP, a plan for bringing these areas back into compliance (attainment). If the air quality in non-attainment areas is not improved, the EPA has the authority to withhold federal highway funds, impose emissions offsets for new industries and/or take over the permitting and enforcement functions of that state.

The National Ambient Air Quality Standards (NAAQS) are one of the federal standards used as a basis for evaluating air quality. The EPA is responsible for reviewing the list of criteria pollutants and their corresponding concentration limits on a five year cycle. Currently, NAAQS ambient concentration limits exist for six criteria pollutants including NOx, SOx, CO, Ozone, PM_{10}, and $PM_{2.5}$. EPA will likely add a NAAQS for PM course ($PM_{10\text{-}2.5}$) in the near future. The current criteria pollutant of interest to the cotton industry is PM_{10}. PM_{10} refers to dust particles that have an aerodynamic diameter less than or equal to 10 micrometers (μm). The primary and secondary 24-hour average NAAQS for PM_{10} is 150 $\mu g/m^3$. The NAAQS also lists a primary and secondary annual average concentration limit for PM_{10} of 50 $\mu g/m^3$.

Agricultural sources of air pollution are coming under increased scrutiny from air pollution regulators. In 2003, California Senate Bill 700 (CARB, 2003) removed all exemptions for agricultural sources from air pollution permitting requirements in California. Further, the serious PM_{10} non-attainment classification for most of the state motivated regulators to impose stringent PM_{10} emission limits on agricultural operations. The agricultural industry can be characterized as having limited and questionable information on PM_{10} emission rates sometimes referred to as emission factors. The current emission factors for agricultural

operations are generally based upon poor science. As a result, several agricultural sources have been identified as large sources of air pollution and have subsequently been targeted for required emissions reductions. Field operations such as land preparation, planting, and harvesting of crops have been identified as large sources of PM_{10} in California.

A limited amount of research has been conducted to quantify the PM_{10} emissions from cotton harvesting. A study conducted under contract with the USEPA by Snyder and Blackwood (1977) reported emissions of particulate matter less than 7 µm (mean aerodynamic diameter) on the order of 0.96 kg/km^2 ($8.4*10^{-3}$ lbs/acre) for harvesting operations using cotton pickers. This emission factor represented the total emission factor from harvesting operations including emissions from the harvesting machine, trailer loading operations, and trailer transporting operations. It was reported by Snyder and Blackwood (1977) that particulate matter samplers followed the harvesting machine at a fixed distance within the plume to collect particulate matter concentrations. The authors stated further that particulate matter concentrations downwind of trailer loading operations were taken by placing samplers at a fixed downwind distance. It is stated in AP-42 (U.S. EPA, 1995) that the emission factors reported are based on the following assumptions:

1. the average speed of the picking machine was 1.34 m/s (3.0 mph),
2. the basket capacity of the picking machine was 109 kg (240 lbs),
3. the capacity of the transport trailers were 6 baskets each, and
4. the average cotton lint yield was 1.17 bales/acre for pickers.

The information given in AP-42 (U.S. EPA, 1995) is based on antiquated harvesting technology and a flawed protocol. It is stated that dust samplers followed the two row picking machines at a fixed distance to determine emission concentrations. No detail is given as to how the researchers used these concentrations to determine the emissions from the harvesting machine. The same is true for the method used to determine the emission rate from the trailer loading operation. Did the researchers use a dispersion model to back-calculate the emission rates from these operations, and if so, which one? Further, the emission factors reported are based on concentrations of particulate matter less than 7 µm mean aerodynamic diameter. This size range of particulate matter represents only part of the regulated size fraction of dust in the US. PM_{10} concentrations include the mass of all particles less than 10 µm in aerodynamic diameter.

The harvesting machinery used to develop the emission factors in AP-42 (U.S. EPA, 1995) does not represent the technology that is used today. Today's machinery can harvest up to 6 rows of cotton per pass with basket capacities in the range of 40 m^3 (1400 ft^3). Clearly, the machines used to harvest the US cotton crop today are significantly different from the machines used in the 1970's, when the Snyder and Blackwood (1977) study was conducted.

Farming practices have also changed resulting in increased yields and field efficiencies since the 1970's. In particular, US cotton production has increased from approximately 10 million bales to around 20 million bales over the last 30 years (USDA, 2005). This is due primarily to improved plant varieties producing higher yields and farming practices that optimize the use of input resources to produce maximum yields. Average annual yields have increased from around 0.85 bales per acre to around 1.5 bales per acre in 2004 (USDA, 2005).

In an effort to quantify the PM_{10} emissions from more modern cotton harvesting operations, Flocchini (2001) conducted a study to measure the emissions from cotton harvesting operations using two to five row equipment. The results of the study by Flocchini (2001) indicate that the PM_{10} emissions from cotton picking machines in the San Joaquin valley of California are on the order of 1.9 kg/ha (1.7 lbs/acre). The protocol used by Flocchini (2001) is summarized as follows:

1. Ambient PM_{10} samplers (Sierra Anderson Model 246b) were used to measure PM_{10} concentrations both upwind and downwind of the harvesting operation.
2. The vertical concentration profile of the dust plume downwind of the operation was quantified using a series of three mobile towers with PM_{10} samplers and anemometers mounted at several heights.

3. A LIDAR instrument was used to help describe the shape of the plume downwind of the harvesting operation. The results of the LIDAR instrument give insight as to the shape of the plume as it travels downwind, but it does not give any reliable indication of the concentration or size of the particulate matter within the plume.
4. A mass balance box model was used with the concentration data to determine the area source emission rate from the operation. Several different methods to describe the shape of the plume were used within the box model to assess the influence of the plume shape on the estimated emission factors.

The work by Flocchini (2001) represents the most up-to-date information regarding PM_{10} emissions from cotton harvesting operations. The sampling protocol used by Flocchini (2001) contained several components that introduced significant levels of uncertainty. The specific areas are:

1. The federal reference method PM_{10} samplers have been shown to exhibit substantial over-sampling errors when sampling agricultural dusts. Buser et al. (2001) indicated that the Federal Reference Method (FRM) PM_{10} sampler could theoretically overstate PM_{10} concentrations by as much as 340% when sampling a dust with MMD and GSD of 20µm and 2.0 respectively. The over-sampling errors reported by Buser et al. (2001) have been observed in field work conducted by several sources including Wanjura et al. (2005) and Capareda et al. (2005).

2. The mass balance box model used to estimate the area source emission rate from the harvesting operation relies on several assumptions pertaining to the height of the plume and depth of the emitting area. In addition, the emission rates determined using the box model are specific to the box model and may not be appropriate to use with another dispersion model. In other words, an emission rate developed with the box model and subsequently used in the box model will return the same measured concentrations initially used to develop the emission rate. However, if the same emission rate is used in another dispersion model, it is likely that the model will not return the measured concentration values. This is important from a regulatory standpoint. ISCST3 is the commonly used dispersion model for regulatory purposes and would be a more appropriate model to use for determining the rate of fugitive emissions from area sources.

Increased regulatory pressure on agricultural industries to reduce emissions are likely to result in undue financial burdens on producers. Increased financial burdens may be encountered in several ways including:

- required implementation of best management practices (BMP) to reduce emissions,
- required improvements to the emission control technologies for stationary sources such as irrigation engines, cotton gins, or grain elevators,
- the replacement of older diesel engines not meeting tighter emission control requirements, and
- increased fees, fines, or expenses encountered in the air quality permitting process.

In order for agricultural sources to be equitably regulated, accurate emissions inventories must be calculated by air pollution regulators using accurate, science-based emission factors. Along with facilitating the equitable regulation of agricultural sources, accurate emissions inventories will help regulators and agricultural producers focus their emissions reduction efforts on the operations or processes that produce the highest level of emissions.

The objective of this manuscript is to describe the conceptual design of a unique sampling system that may be used to take isokinetic measurements of PM emissions from a cotton picker. It is expected that a more accurate emission factor for cotton harvesting operations may be developed from isokinetic PM emission measurements than from the previous protocols described by Flocchini (2001) and Snyder and Blackwood (1977).

Methods

Conceptual Sampler Design

Initial conceptual designs of the harvester sampling system pointed out several specific design criteria that must be considered from the standpoint of functionality and safety. The primary design criteria identified are:

1. The design must effectively collect all of the air, seed cotton, and foreign material into one unit where the seed cotton and large trash will be separated from the air and entrained particulate matter.
2. The seed cotton and large foreign material will be dropped into the basket of the machine through a set of air-tight paddle wheels while the air and entrained particulate matter will be exhausted through one common exit point.
3. The mechanism by which the air and seed cotton/large foreign material are separated must be designed so to prevent the occurrence of material "plugging" which could lead to mechanical failure, fire, or other damage to the harvester or harvested material.

The harvester design and performance data used in this analysis were obtained from Deere and Co. (personal communication with Robert Bares, April 1, 2005) for the 9996 and 9986 six row cotton pickers. It is expected that the same sampler design process could be repeated for other makes and models of cotton pickers.

The John Deere 9986 and 9996 six row cotton pickers use a single centrifugal fan to produce the airflow necessary for pneumatically conveying the harvested seed cotton from the picking units to the basket. Approximately 736 m^3/min (26,000 ft^3/min) of air is exhausted from the six transport tubes that carry the harvested material from the picking units to the basket. The harvested material is separated from the air stream by a set of finger grates located at the top of the basket. The proposed sampling system would collect all of the air and seed cotton exhausted from the conveying ducts at the point where the harvested material would normally be separated from the air stream by the finger grates. The seed cotton and large trash will be separated from the air stream via a set of baffles on the inside of the dropper box. The air stream and entrained particulate matter will be exhausted through one common exit at the rear of the dropper box while the seed cotton and large trash will be dropped into the picker basket through a set of air-tight paddle wheels. The air exit of the dropper box will have a cross sectional area of 0.537 m^2 (5.78 ft^2) to move the air at the minimum conveying velocity (1372 m/min = 4500 ft/min) required to maintain the entrainment of the particulate matter in the exhaust air. Isokinetic sampling probes will be placed at two locations in the air duct just before the exhaust point to the outside. The isokinetic samplers will each pull a sample flow rate of 1.42 m^3/min (50 ft^3/min) of the total 736 m^3/min (26,000 ft^3/min) exhausted. At the 1.42 m^3/min (50 ft^3/min) sampling flow rate, the nozzle diameter of the isokinetic sampling probe must be 3.63 cm (1.43 in) to maintain the same air velocity entering the sampling nozzle as the velocity of the air passing it. The sampled air stream will be passed through a barrel cyclone separator to remove the majority of the particulate matter from the air stream while the remaining fine particulate mass is captured on a filter. Both the mass of the particulate matter on the filter and the mass of particulate matter collected from the bottom side of the cyclone will be used to determine the TSP emission rate of the dust entrained in the air exhausted from the harvester. The total suspended particulate emission rate can be calculated according to equation 1.

$$ER_{TSP} = \frac{M_F + M_C}{Q_S T} Q_T \quad (1)$$

where:

ER_{TSP} = TSP emission rate (kg/min),

$M_{F,C}$ = net particulate mass captured on the filter and particulate mass collected from the bottom side of the cyclone (kg),

$Q_{S,\ T}$ = isokinetic sampling (S) flow rate (1.42 m^3/min) and total (T) exhaust air flow rate (736 m^3/min), and

T = test duration (min).

The calculation of the emission factor on a per bale harvested basis can be done by dividing the emission rate (kg/min) by the seed cotton harvesting rate (kg of seed cotton/min) as measured by an onboard yield monitor. The assumption that 636 kg (1400 lbs) of seed cotton are required to produce a 227 kg (500 lb)

bale of lint may be used for preliminary data reporting. However, gin-out data of the cotton harvested should be used to validate and correct the preliminary turnout data to determine final emission factors.

The TSP emission factor of the cotton harvesting operation can also be reported on a per acre harvested basis. GPS data taken from the onboard yield monitor will be used to determine the land area harvested per unit time. This emission factor will be calculated by dividing the total mass of particulate matter emitted by the harvester per test by the total land area harvested per test.

Final PM_{10} emission factors may be calculated from the original TSP emission factors by applying the results of particle size distribution analyses of the particulate matter collected on the filters and from the bottom side of the cyclone. The particle size distribution (PSD) of agricultural particulate matter can be described by a lognormal distribution relating percent mass to particle diameter. This lognormal particle size distribution is characterized by the mass median diameter (MMD) and the geometric standard deviation (GSD). The Coulter Multisizer III (Beckman – Coulter, Coulter Multisizer III, Miami, FL) and the Malvern Mastersizer 2000 (Malvern Instruments, Mastersizer 2000, Worcestershire, United Kingdom) will be used to perform the particle size distribution analyses. Past work using these two instruments indicates very good agreement between the results from the two instruments (Simpson et al., 2003). The analysis protocol used with the Coulter instrument suspends the particulate matter from the filter media in a 5% Lithium Chloride – Methanol solution. Reliable particle size distributions can be obtained from particulate matter samples of mass as low as 200 µg. The Malvern instrument has the capability to analyze samples suspended in an ethanol based solution or as a dry sample suspended in air.

Both the Coulter and Malvern instruments report particle diameters in terms of equivalent spherical diameter (ESD). As noted above, particulate matter regulations are based on aerodynamic particle diameter. ESD can be converted to aerodynamic diameter by equation 2.

$$D_A = ESD\sqrt{\rho_P} \tag{2}$$

where:

D_A = aerodynamic diameter (µm),
ESD = equivalent spherical diameter (µm), and
ρ_P = particle density (g/cm^3).

Particle density analyses will be performed on the particulate matter collected from the bottom side of the cyclone.

The percent of the particulate mass less than 10 µm aerodynamic equivalent diameter will be weighted by the mass of the sample from which it was taken and averaged to give the total mass percent less than 10 µm for the test. This mass percent will be multiplied by the TSP emission factor to give the final PM_{10} emission factor. The weighted average procedure to determine the average percent less than 10 µm is shown by equation 3.

$$AvgPM_{10} = \frac{M_F(PM\ 10_F) + M_C(PM\ 10_C)}{M_F + M_C} \tag{3}$$

where:

$AvgPM_{10}$ = weighted average percent PM_{10} from the particulate matter collected on the filter and from the bottom side of the cyclone (%),
$PM10_{F,C}$ = Percent of particulate mass less than 10 µm captured on the filter (F) and cyclone (C) respectively.

A spreadsheet model was developed to simulate the operation of the proposed sampling system. Several assumptions were made about the input parameters including:

- crop row spacing of 102 cm (40 in),
- 636 kg (1400 lbs) of harvested seed cotton are required to produce one 227 kg (500 lb) bale of lint,
- the 6 row harvester moves through the field at 6.44 km/h (4 mph),
- the mass of seed cotton harvested per test is 2270 kg (5000 lbs), and
- the barrel cyclone used in the sampling system has an efficiency of 97%.

The model was used to predict the sampling time, net filter mass, and PM_{10} emission factor (lbs/ac and lbs/bale) for several different scenarios. The input variables that were changed to observe the change in the output parameters are shown in table 1. For each of the scenarios, only one parameter was changed while the other variable parameters were held at their base case values. The parameter values used for the base case scenario are indicated with an asterisk.

Table 1. Input parameter values for the sampling system simulation model.

Input Parameter	Values
TSP Emission Factor (lbs/ac)	10, 20*, 30, 40
MMD of Dust Emitted From the Harvester (□m)	25, 30*, 35
GSD of Dust Emitted From the Harvester	1.8, 2.0*, 2.5
Crop Yield (bales/ac)	2, 2.5*, 3

*Base case value.

Results

The results of the base case scenario indicated that the sampling time (time to harvest 2270 kg of seed cotton) from cotton yielding 2.5 bales/ac with a TSP emission factor of 22.4 kg/ha (20 lbs/ac) (MMD = 30μm, GSD = 2.0) was 10.6 min. The mass of particulate matter collected on the filter was 0.75 g and the PM_{10} emission factors were 1.27 kg/ha and 0.20 kg/bale (1.13 lbs/ac and 0.45 lbs/bale).

Table 2 presents the results of changing the crop yield in the model from 2 to 3 bales per acre. As expected, the sampling time decreased with increasing yield. The increased yields resulted in an increased harvesting rate (bales/min) thus reducing the time to harvest 2270 kg (5000 lbs) of seed cotton. Similarly, the net filter mass and PM_{10} emission factor (kg/bale) decreased with increasing yield while the PM_{10} emission rate (kg/ha) remained constant. This result was due to the constant TSP emission rate of 22.4 kg/ha (20 lbs/ac).

Table 2. Harvester sampler simulation results with varying crop yield.

	Crop Yield (Bales/ac)		
	2	**2.5**	**3**
Sampling Time, min	13.3	10.6	8.8
Net Filter Mass, g	0.94	0.75	0.62
PM_{10} Emission Factor, kg/ha (lbs/ac)	1.27 (1.13)	1.27 (1.13)	1.27 (1.13)
PM_{10} Emission Factor, kg/bale (lbs/bale)	0.25 (0.55)	0.20 (0.45)	0.17 (0.37)

The results of varying the TSP emission factor (kg/ha) in the model are shown in table 3. The sampling time is shown to be constant because the yield is constant at 2.5 bales/ac. As anticipated, the net filter mass and PM_{10} emission factors (kg/ha and kg/bale) all increased as the TSP emission factor increased. This result is due to the assumption that the dust emissions are constant over a given area and are not dependent upon yield. The validity of this assumption will be investigated further in future work.

Table 3. Harvester sampler simulation results with varying TSP emission factor.

	TSP Emission Factor, kg/ha (lbs/ac)			
	11.2 (10)	**22.4 (20)**	**33.6 (30)**	**44.8 (40)**
Sampling Time, min	10.6	10.6	10.6	10.6
Net Filter Mass, g	0.37	0.75	1.12	1.5
PM_{10} Emission Factor, kg/ha (lbs/ac)	0.63 (0.56)	1.27 (1.13)	1.91 (1.7)	2.54 (2.26)
PM_{10} Emission Factor, kg/bale (lbs/bale)	(0.23)	(0.45)	(0.68)	(0.9)

The maximum net filter mass (for any of the scenarios) is 1.5 g for the scenario using a TSP emission factor of 44.8 kg/ha (40 lbs/ac) (table 3). This result is important to the design of the sampling system because increasing net filter mass increases the static pressure loss across the filter media. Previous work has

shown that a maximum net particulate mass of approximately 1.5 g (3.3 x 10^{-3} lbs) can be captured on a glass fiber filter while maintaining the desired sampling flow rate through the system. However, glass fiber filters have been shown to contribute significant numbers of background particles when performing particle size distributions on filter core samples cut from glass fiber filter media. Teflon membrane filters used for particle size distribution analyses have shown negligible background particle counts. However, the Teflon membrane filters have a substantially higher static pressure loss than a glass fiber filter for a given filter face velocity (filter face velocity = sampling flow rate / filter area). The ideal filter media for implementation in this protocol will have the following characteristics: 1) the material will be hydrophobic, 2) the material will have a low static pressure loss, 3) the filter media will exhibit low background particle counts in particle size distribution analyses on filter cores cut from the original material, and 4) the material will be cost effective. Different filter media will be evaluated for the given criteria and the best material or combination of materials will be used for concentration and particle size distribution analyses. This is to say that one filter material may be used for concentration analysis only and another material for particle size distribution analysis.

The results of varying the particle size distribution of the dust emitted from the harvester are shown in tables 4 and 5. The results indicate that with a constant crop yield and TSP emission factor, the sampling time and net filter mass will remain constant. However, the PM_{10} emission factors (kg/ha and kg/bale) decrease as the MMD of the dust emitted from the harvester increases (table 4). Conversely, the PM_{10} emission factors increase as the GSD of the dust increases (table 5).

Table 4. Harvester sampler simulation results with varying MMD of the dust emitted from the harvester.

	MMD of Dust Emitted from Harvester (µm)		
	25	**30**	**35**
Sampling Time, min	10.6	10.6	10.6
Net Filter Mass, g	0.75	0.75	0.75
PM_{10} Emission Factor, kg/ha (lbs/ac)	2.09 (1.86)	1.27 (1.13)	0.8 (0.71)
PM_{10} Emission Factor, kg/bale (lbs/bale)	0.34 (0.74)	0.204 (0.45)	0.13 (0.28)

Table 5. Harvester sampler simulation results with varying GSD of the dust emitted from the harvester.

	GSD of Dust Emitted from Harvester		
	1.8	**2**	**2.2**
Sampling Time, min	10.6	10.6	10.6
Net Filter Mass, g	0.75	0.75	0.75
PM_{10} Emission Factor, kg/ha (lbs/ac)	0.7 (0.62)	1.27 (1.13)	1.84 (1.64)
PM_{10} Emission Factor, kg/bale (lbs/bale)	0.11 (0.25)	0.204 (0.45)	0.3 (0.65)

Relatively little work has been conducted to characterize the PSD of the dust emitted from cotton harvesting operations. It is expected that the dust emitted from the harvester will be predominately influenced by soil, organic material, environmental conditions prior to harvest. Research work is planned for 2006 to characterize the PSD of the dust emitted from cotton harvesting machines. The planned work will use seed cotton and soil samples taken from several areas in Texas and New Mexico. Approximately half of the seed cotton samples have been taken from harvesting operations using cotton pickers and the other half using cotton strippers. The objectives of the planned work are to characterize the PSD of the dust emitted from the harvesters and also to quantify the proportions of soil and organic matter in the PM emitted.

Conclusions

The design concepts of the sampling system discussed in this manuscript suggest that it may be possible to develop a more accurate science based emission factor based on isokinetic PM concentration samples and subsequent particle size distribution analyses. This novel concept has never been applied to sampling

emissions from field operations of any kind. The main benefits of the proposed sampling system and methodology are:

- PM emission concentrations are measured directly from the source,
- PSD analysis to characterize the percent mass vs. particle diameter relationship can be used to accurately quantify emission factors based on any size indicator (i.e. $PM_{2.5}$, PM_{10}, or $PM_{10-2.5}$), and
- Resulting emission factors are not based on downwind ambient concentrations measured with flawed samplers or inaccurate dispersion models.

It is expected that downwind concentration measurements will be taken and used with an EPA approved dispersion model (ISCST3 or AERMOD) to back calculate the area source emission factor for comparison with the emission factor developed from the source sampling technique discussed here. In addition, the emission factor developed from the source sampling technique described in this manuscript will be used in an EPA approved dispersion model to evaluate the downwind effects of the harvester emissions.

As were pointed out here, there are many assumptions that need to be validated and corrected through future laboratory and field testing. The design, fabrication, and testing of the cotton harvester sampling system is planned for 2007. If the proposed source sampling technique is shown to be effective and accurate, it is expected that the same concepts could be applied to several other harvesting machines including almond orchard harvesters, grain combines, etc.

Disclaimer

Mention of a trade name, propriety product or specific equipment does not constitute a guarantee or warranty by the United States Department of Agriculture and does not imply approval of a product to the exclusion of others that may be suitable.

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