


Collocating Specialty Crops and Solar panels in Alabama, Southeastern USA

Bijesh Mishra ^{1,*}, Ngbede Musa¹, Paul Mwebaze², Madhu Khanna², James McCall³, and
Ruiqing Miao¹

¹Auburn University, Auburn, AL, 36849

²University of Illinois Urbana-Champaign, Urbana, IL, 61801

³National Renewable Energy Lab, Denver, CO, 80401

*Corresponding author: bzm0094@auburn.edu

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Solar energy generation in the United States (US) has increased by threefold from 2017 to 2022 (Hodge, 2023) and expected to increase as US government aimed to achieve 100% carbon-free electricity by 2035 (Department of Energy, 2023) to fight against climate change (Gomez-Casanovas et al., 2023; Mamun et al., 2022). Solar energy production in agricultural land is expected to expand in the future (Department of Energy, 2023) resulting into land use conflict between solar energy and food productions. The median solar potential is highest in agricultural land because of higher radiance and favorable micro-climatic factors such as wind speed, relative humidity, isolation, and air temperature (Adeh et al., 2019). Collocating solar panels with agricultural crops—agrivoltaic system—is an innovative approach to minimize the conflict between energy and food production (Macknick et al., 2022; Pascaris et al., 2022). The agrivoltaic system, however, creates a unique condition where the trade-off between land use for crops and solar panels is unavoidable. Producers face a land allocation problem and fluctuation in crop yield as the land allocated for crop production decreases with the increase in land allocated for solar panels. The lower wind energy potential (NREL, 2011), high solar energy potential (Sengupta et al., 2018), and plenty of agricultural lands in the southeastern US makes agrivoltaic a viable choice for clean energy and food production in this region. In this study we estimated profit from tomato, strawberry, and squash agrivoltaic systems under various solar densities and further explored minimum crop yields necessary to achieve better profit from agrivoltaic systems compared to the crop alone.

Tomato, strawberry, and squash have economic, tourism, and cultural significance in the US and Alabama. Approximately 35 billion pounds of tomato was produced in the US with total economic impact of more than 2.6 billion in 2015 (Guan et al., 2018). Tomato was produced in 712 farms in Alabama in 2007 (Duzy et al., 2014). Strawberry is relatively new crops in Alabama which was produced in 44 hectares of farmland generating \$339,000 revenue in 2019 (Hernández-Martínez et al., 2023). The US grew \$149 million-dollar worth squash in 2019 in 45,000 acres of agricultural land. Southern states are one of the major producers of squash with its market expanded throughout the US (Agriculture Market Resource Center, 2024). Even though tomato, strawberry, and squash are grown in small share of land in Alabama, they are important crops produced in backyard vegetable gardens, supporting local economy, agri-tourism, supply fresh local products, vitalize local farmer’s market, and provide revenue sources to small and family farms throughout the state of Alabama (Sweet Grown Alabama, 2024; Velasco, 2024). Farmers often invite visitors for vegetable picking, sell products in local farmers markets, and provide farming experience to local community while generating continuous revenue stream.

Extreme weather and pressure from pests and diseases are the biggest threats for vegetable production in Alabama (Hernández-Martínez et al., 2023). Climate change

will increase the frequency of overheating and drought that have severe impact in the production of specialty crops (Cammarrano et al., 2022), reduces the post harvest quality (Moretti et al., 2010), and increases insect pest infestation (Litskas et al., 2019). The increase in temperature by 3 to 6 degree Celsius would negatively affect the suitability of economically viable crops such as tomato and squash, pushing them to marginal and very marginal crops categories (Ngoy & Shebitz, 2020). Solar panels in agrivoltaic systems provides shade which have potential to reduce the negative impacts of climate change on specialty crops and improve water efficiency (Al-agele et al., 2021; Barron-Gafford et al., 2019; Walston et al., 2018).

In rest of the article we will explain the agrivoltaic system configurations and estimation methods followed by the the profit from three crops at observed yield (Boswell et al., 2023) combined with various proportion of land allocated for solar energy system. We further discuss the minimum yield for three crops required to achieve higher profit from agrivoltaic system than the crop alone at various electricity and crop prices and solar system configurations for four regions of Alabama.

We estimated cost, revenue, and profit of three specialty crops—tomato, strawberry, and summer squash—agrivoltaic systems in one acre square-shaped plot for northern, central, black belt, and southern Alabama. We allocated one acre of land for solar energy and food production such that our estimation can be used as energy and food production from larger land that has multiple plots of an acre lands. We used non-transparent standard solar panels with 7.75 feet (ft.) length by 3.5 ft. width which cast shadow on the ground based on the rotation of the sun. We considered two south oriented array type—fixed tilt open rack (fixed) and single axis tracking (tracking)—solar panels mounted at 4.6 ft., 6.4 ft., and 8.2 ft. high from the ground following module specifications specified in PV Watt Calculator (Dobos, 2014). We considered six capital expenditure costs (CAPEX) based on panel height and array types (Fig: 1). Solar panel density was varied from 0% to 100%. The edge to edge distance between successive rows of solar panels at 100% solar density was 6 ft. The spacing between rows increases with the decrease in solar panel density. Plots with 0% solar densities have crops but lacks solar panels. We estimated system annual energy output using PV Watt Calculator (Dobos, 2014) and multiplied the energy output by three energy prices (\$0.02, \$0.03, and \$0.04 per kilowatt-hour (kWh)) to estimate annual revenue from solar. The CAPEX was annualized at 5% compound interest rate for 25 years of solar panel’s lifespan and subtracted from the annualized energy revenue to get total profit from total solar energy production.

We obtained tomato, strawberry, and summer squash plantation cost and crop yield from Alabama A&M and Auburn Universities Extension System Enterprise budget (Boswell et al., 2023). We varied crop yield from 10% to 200% of the total yield assuming total yield in the enterprise budget is 100% yield for three crops because the effect of interaction between crops and solar panels on crop yield in agrivoltaic system is unknown

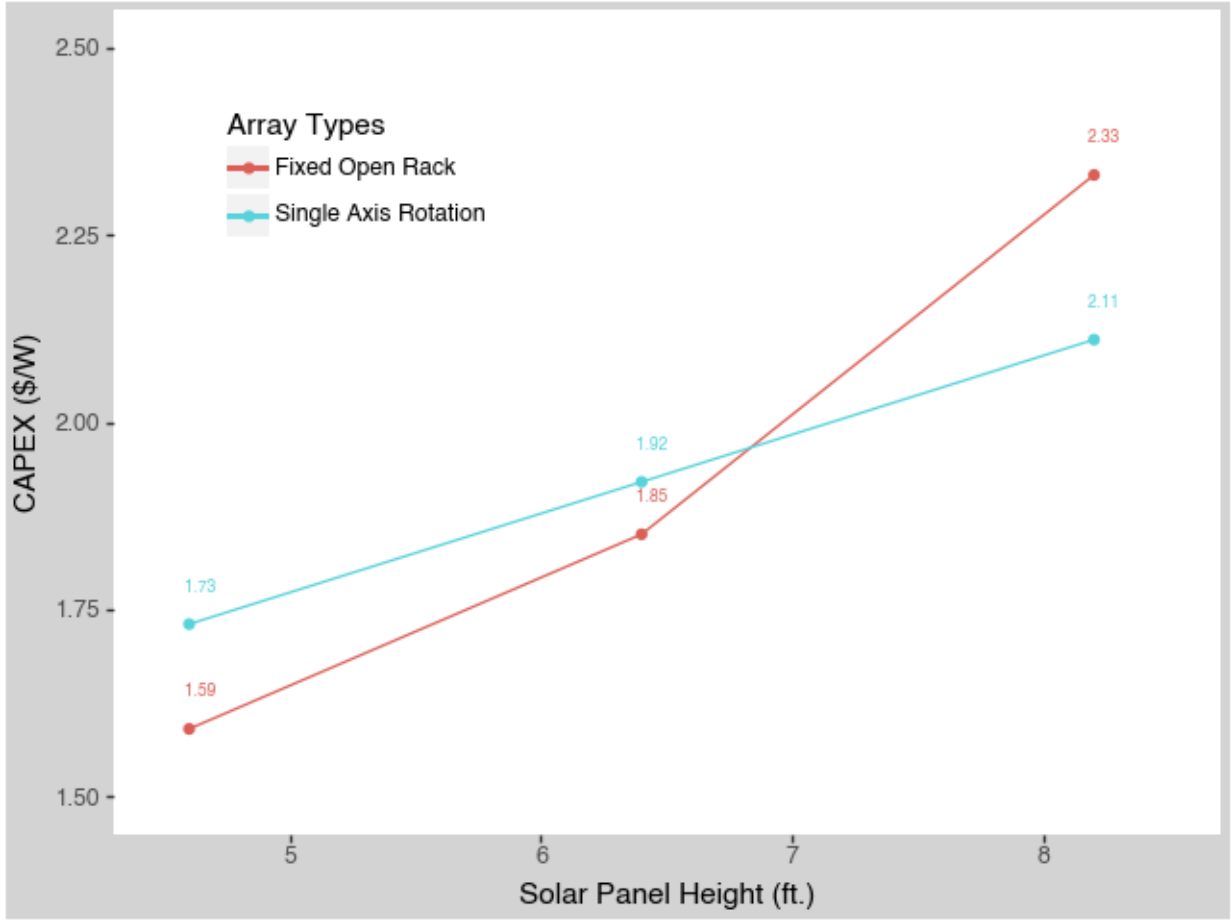


Figure 1: CAPEX for agrivoltaic systems with fixed open rack and single rotation axis array solar panel systems at 4.6 ft, 6.4 ft. and 8.2 ft. clearance height above the ground. The CAPEX were estimated following Horowitz et al. (2020) and the CAPEX for 6.4 ft. single axis rotation panel was predicted using panel capex, panel heights, and array types.

(Gomez-Casanovas et al., 2023). For example, the shadow from solar panels can have positive effect of reducing heat (Othman et al., 2020) and water stresses (Omer et al., 2022) and increase disease resistance capacity (Willockx et al., 2022) but could reduce the yield (Al-agele et al., 2021; Weselek et al., 2021) because of reduced sunlight. The effect of shadow on soil quality and soil microbial compositions could change crop production in agrivoltaic system (Mamun et al., 2022). This approach allows us to estimate various combinations of solar panels and crops at which the profit from agrivoltaic system exceeds the profit from crop alone at the given crop prices. We estimated profits of tomato sold at \$17 to \$23 at \$1 increment per 25 pound (lb) carton, strawberry sold at \$3 to \$9 at \$1 increment per bucket, and summer squash sold at \$22 to \$28 at \$1 increment per bushel (bu) carton. We varied harvest labor and harvest container cost in the enterprise budget (Boswell et al., 2023) proportionate to the change in crop yield. We further assumed that crop plot size is not limited by co-locating solar panels and crops because solar panels are mounted on metallic poles at least 4.2 ft. high which was sufficient to accommodate cultural operations and achieve the plant maturity height for three crops.

We added profit from solar and crop to estimate joint profit from agrivoltaic systems for all combinations of twenty-one solar proportions (0% to 100% at 0.05% increment), two arrays, three solar panel heights, three energy prices, twenty crop yields (10% to 200% of original yield (100%) at 10% increment), and seven crop prices for four regions (Northern, Central, Black Belt and Southern) of Alabama. This process was repeated for agrivoltaic systems with three crops separately.

Tomato Agrivoltaic system

The profit from 3,075 25lb buckets tomato produced per acre priced at \$17 per bucket was \$9,619.38 (Table 1). The profit from tomato agrivoltaic system per acre land at the above price and yield ranged from \$13,054.61 to \$30,942.13 depending upon solar panel density, panel heights, solar array types, and geographical regions. The profit from tracking panels were higher compared to fixed panels in all scenarios. The profit from agrivoltaic system increased from north to south because of increase in solar energy production. The profit increased with the increase in solar panel density but decreased with the increase in solar panel height and the profit differences among three panel heights were very small.

Solar Proportion (Total Panels) →		0% Solar			25 % Solar (177 Panels)			50% Solar (413 Panels)			75% Solar (590 Panels)			100% Solar (885 Panels)		
Solar Panel Height (ft.) →	Array ↓	4.6	6.4	8.2	4.6	6.4	8.2	4.6	6.4	8.2	4.6	6.4	8.2	4.6	6.4	8.2
Regions ↓																
North	Fixed	9619.38	13054.61	13053.07	13050.18	17633.19	17629.59	17622.85	22212.66	22207.00	22196.42	26792.08	26784.36	26769.93		
Central	Fixed	9619.38	13179.50	13177.96	13175.07	17924.46	17920.86	17914.12	22670.34	22664.68	22654.10	27416.20	27408.48	27394.05		
Black Belt	Fixed	9619.38	13261.16	13259.62	13256.73	18114.54	18110.94	18104.20	22969.05	22963.39	22952.81	27823.54	27815.82	27801.39		
South	Fixed	9619.38	13290.71	13289.17	13286.28	18183.72	18180.12	18173.38	23077.74	23072.08	23061.50	27971.74	27964.02	27949.59		
North	Tracking	9619.38	13550.75	13549.62	13548.48	18791.59	18788.95	18786.31	24032.77	24028.61	24024.46	29273.94	29268.28	29262.61		
Central	Tracking	9619.38	13737.71	13736.58	13735.44	19227.70	19225.06	19222.42	24718.03	24713.87	24709.72	30208.38	30202.72	30197.05		
Black Belt	Tracking	9619.38	13829.87	13828.74	13827.60	19442.68	19440.04	19437.40	25055.89	25051.73	25047.58	30669.06	30663.40	30657.73		
South	Tracking	9619.38	13886.75	13885.62	13884.48	19575.40	19572.76	19570.12	25264.45	25260.29	25256.14	30953.46	30947.80	30942.13		

Table 1: Profit from tomato agrivoltaic system. Tomato was priced at \$20 per 25lb bucket for 3,075 buckets. Electricity was priced at \$0.03/kWh. The profit from 0% solar was based on the profit from strawberry only. Source: Authors.

We found that tomato AV become more profitable than tomato at 1,360 bucket yield per acre when 10% land is allocated for solar panels in virtually all combinations of crop prices, electricity prices, land proportions, array, heights, and regions of Alabama (Figure 2). The yield requirement generally decreased with the increase in land allocation for solar energy production, price of electricity, and price of crops. At 10% land allocation for solar, \$17 tomato price, and \$0.04 electricity price the yield requirement decreased to 1,224 bucket in black belt and southern Alabama for all three heights and two tracking system. The yield was equivalent to allocating up to 45% land for fixed array agrivoltaic systems, \$0.02/kWh electricity price, and \$23/bucket tomato price in the central, black belt, and southern regions. When 70% land allocated to tracking array solar panels, \$17 tomato price, and \$0.03 energy price in northern Alabama, the minimum yield required for tomato agrivoltaic to become more profitable than tomato alone is 272 bucket which is equivalent to allocating 80% of land for solar panels with fixed array panels without changing other

parameters. This yield condition can be achieved in black belt and southern Alabama when 50% land is allocated for solar for both arrays for the same price of tomato and \$0.04 electricity price. The yield requirement for tomato agrivoltaic system to be more profitable than tomato alone are plotted in figure 2 for various solar system configurations and energy and crop prices.

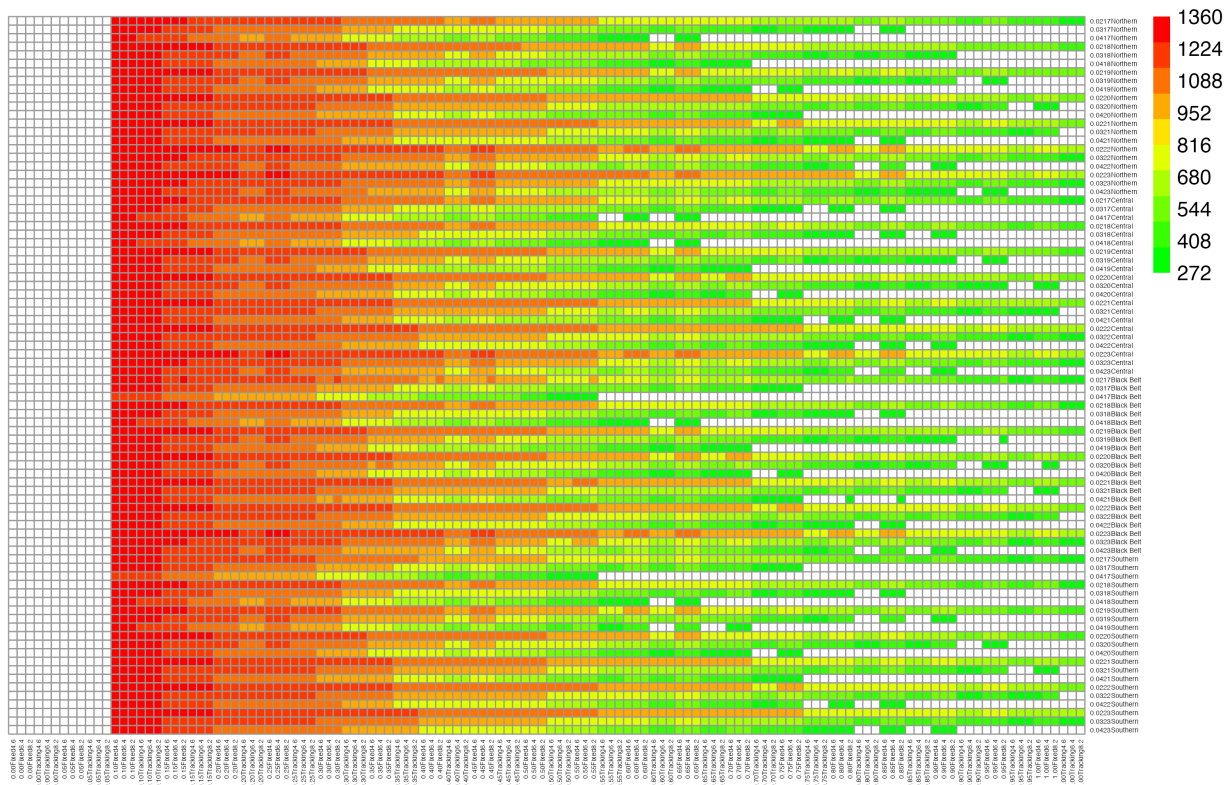


Figure 2: Tomato yield (25lb buckets) at which the difference in the profit from tomato agrivoltaic and the profit from tomato alone is positive for the tomato agrivoltaic system with the given specifications. The vertical axis consists of electricity price (\$/kWh), tomato price, and regions of Alabama. The label on the first row, 0.0217Northern, consists of \$0.02/kWh electricity price, \$17 tomato price, and Northern region of Alabama. There are three electricity prices, seven tomato prices (\$17, \$18, \$19, \$20, \$21, \$22, and \$23), and four regions of Alabama. The horizontal axis consists of proportion of land covered by solar panels, solar panel array types, and solar panel ground clearance height (ft.). The label on the first column, 0.00Fixed4.6, consists of 0.00% land under solar panels, fixed tilt solar panels facing south, and solar panels mounted 4.6 ft. above the ground. White squares lack data because either the profit from tomato agrivoltaic was less than that from tomato alone (left side) or smallest yield was identified where the difference between tomato agrivoltaic profit and tomato profit alone is greater than zero (right side). Source: Authors.

Strawberry Agrivoltaic system

The Profit from 1,360 buckets strawberry produced per acre land and priced at \$9 per bucket was \$10,940.96 (Table 2). The profit from strawberry agrivoltaic system per acre land at the same price and yield ranged from \$14,376.18 to \$32263.71 depending upon

solar panel density, panel heights, solar array types, and geographical regions. The change in profits from strawberry agrivoltaic follow same pattern as tomato agrivoltaic for the variations in solar panel density, geography, arrays, and panel heights.

Solar Proportion (Total Panels) →		0% Solar	25 % Solar (177 Panels)			50% Solar (413 Panels)			75% Solar (590 Panels)			100% Solar (885 Panels)		
Solar Panel Height (ft.) →	Array ↓		4.6	6.4	8.2	4.6	6.4	8.2	4.6	6.4	8.2	4.6	6.4	8.2
Regions ↓														
North	Fixed	10940.96	14376.18	14374.64	14371.75	18954.76	18951.16	18944.42	23534.24	23528.58	23517.99	28113.65	28105.93	28091.50
Central	Fixed	10940.96	14501.07	14499.53	14496.64	19246.03	19242.43	19235.69	23991.92	23986.26	23975.67	28737.77	28730.05	28715.62
Black Belt	Fixed	10940.96	14582.73	14581.19	14578.30	19436.11	19432.51	19425.77	24290.63	24284.97	24274.38	29145.11	29137.39	29122.96
South	Fixed	10940.96	14612.28	14610.74	14607.85	19505.29	19501.69	19494.95	24399.32	24393.66	24383.07	29293.31	29285.59	29271.16
North	Tracking	10940.96	14872.32	14871.19	14870.06	20113.17	20110.52	20107.88	25354.34	25350.19	25346.03	30595.51	30589.85	30584.19
Central	Tracking	10940.96	15059.28	15058.15	15057.02	20549.28	20546.63	20543.99	26039.60	26035.45	26031.29	31529.95	31524.29	31518.63
Black Belt	Tracking	10940.96	15151.44	15150.31	15149.18	20764.26	20761.61	20758.97	26377.46	26373.31	26369.15	31990.63	31984.97	31979.31
South	Tracking	10940.96	15208.32	15207.19	15206.06	20896.98	20894.33	20891.69	26586.02	26581.87	26577.71	32275.03	32269.37	32263.71

Table 2: Profit from strawberry agrivoltaic system. Strawberry was priced at \$9 per bucket for 1,360 buckets. Electricity was priced at \$0.03/kWh. The profit from 0% solar is based on the profit from tomato only. Source: Authors.

The yield at which profit from strawberry agrivoltaic was great than the strawberry alone was highly influenced by the electricity price (Figure 3). For example, at \$0.02 electricity price, and \$3 strawberry price, the yield required was 2,767.5 bucket but at \$0.04 electricity price the yield required for the difference to become positive was 2,460 bucket for 10% land allocated to solar panels in all three heights and two array types in northern Alabama. At \$4 strawberry price with above system specifications in Northern Alabama, the yield requirements were 3075 and 2767.5 at \$0.03 kWh and \$0.04 kWh energy prices. The trend was consistent across four regions of Alabama. At \$7, \$8, and \$9 strawberry per bucket, the yield requirement did not change even though price of electricity changed for all two arrays and three heights at 10% land allocation for solar panels. The above trend continued, however, for three prices when 15% or more land was allocated for solar panels. The yield requirement however decreases for higher proportion of land allocation for solar panels. The smallest yield, 615 buckets, required to achieve higher profit from strawberry agrivoltaic compared to strawberry alone in central, black belt and southern regions were by allocating 20% land to solar energy production using fixed panels for all three heights and selling electricity at \$0.04 kWh and strawberry at \$3 per bucket and 25% land is required in northern region to get same yield level. The yield requirement for strawberry agrivoltaic system to be more profitable than strawberry alone are plotted in figure 3 for various solar system configurations and energy and crop prices.

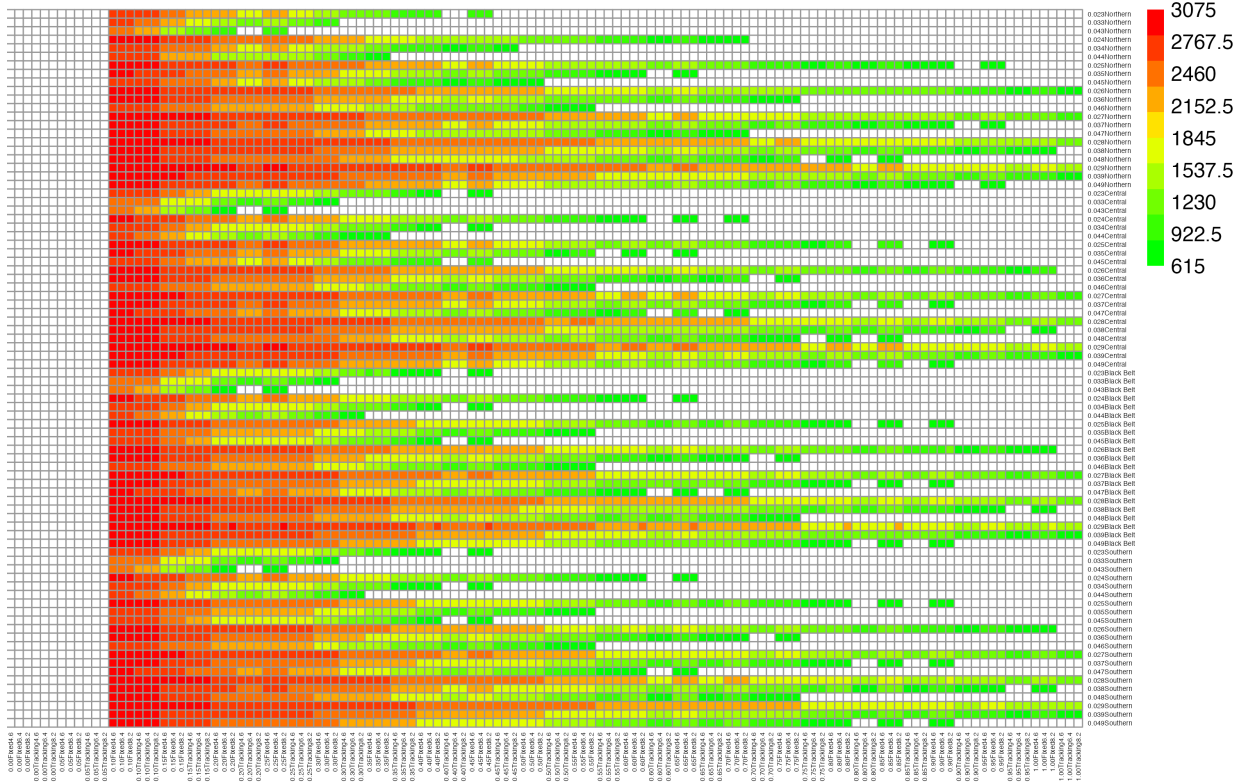


Figure 3: Strawberry yield (buckets) at which the difference in the profit from strawberry agrivoltaic and the profit from strawberry alone is positive for the strawberry agrivoltaic system with the given specifications. The vertical axis consists of electricity price (\$/kWh), strawberry price, and regions of Alabama. The label on the first row, 0.023Northern, consists of \$0.02/kWh electricity price, \$3 strawberry price, and Northern region of Alabama. There are three electricity prices, seven strawberry prices (\$3, \$4, \$5, \$6, \$7, \$8, and \$9), and four regions of Alabama. The horizontal axis consists of proportion of land covered by solar panels, solar panel array types, and solar panel ground clearance height (ft.). The label on the first column, 0.00Fixed4.6, consists of 0.00% land under solar panels, fixed tilt solar panels facing south, and solar panels mounted 4.6 ft. above the ground. White squares lack data because either the profit from strawberry agrivoltaic was less than that from strawberry alone (left side) or smallest yield was identified where the difference between strawberry agrivoltaic profit and strawberry profit alone is greater than zero (right side). Source: Authors.

Summer Squash Agrivoltaic system

The Profit from 1,090 bushel squash produced per acre priced at \$34 per bushel was \$9,831.62 (Table 3). The profit from squash agrivoltaic per acre ranged from \$14,376.18 to \$32263.71 at the above yield and price depending upon solar panel density, panel heights, solar array types, and geographical regions. The change in profit from squash agrivoltaic system increased with the increase in solar density, decreased with the increase in solar panel heights. The profit is higher in the southern Alabama compared to northern Alabama and for rotating array compared to fixed array of solar panels.

Solar Proportion (Total Panels) →		0% Solar			25 % Solar (177 Panels)			50% Solar (413 Panels)			75% Solar (590 Panels)			100% Solar (885 Panels)		
Solar Panel Height (ft.) →	Array ↓	4.6	6.4	8.2	4.6	6.4	8.2	4.6	6.4	8.2	4.6	6.4	8.2	4.6	6.4	8.2
Regions ↓																
North	Fixed	9831.62	13266.85	13265.30	13262.42	17845.42	17841.82	17835.09	22424.90	22419.24	22408.66	27004.31	26996.60	26982.16		
Central	Fixed	9831.62	13391.74	13390.19	13387.31	18136.69	18133.09	18126.36	22882.58	22876.92	22866.34	27628.43	27620.72	27606.28		
Black Belt	Fixed	9831.62	13473.40	13471.85	13468.97	18326.77	18323.17	18316.44	23181.29	23175.63	23165.05	28035.77	28028.06	28013.62		
South	Fixed	9831.62	13502.95	13501.40	13498.52	18395.95	18392.35	18385.62	23289.98	23284.32	23273.74	28183.97	28176.26	28161.82		
North	Tracking	9831.62	13762.98	13761.85	13760.72	19003.83	19001.19	18998.54	24245.00	24240.85	24236.70	29486.17	29480.51	29474.85		
Central	Tracking	9831.62	13949.94	13948.81	13947.68	19439.94	19437.30	19434.65	24930.26	24926.11	24921.96	30420.61	30414.95	30409.29		
Black Belt	Tracking	9831.62	14042.10	14040.97	14039.84	19654.92	19652.28	19649.63	25268.12	25263.97	25259.82	30881.29	30875.63	30869.97		
South	Tracking	9831.62	14098.98	14097.85	14096.72	19787.64	19785.00	19782.35	25476.68	25472.53	25468.38	31165.69	31160.03	31154.37		

Table 3: Profit from summer squash agrivoltaic system. Squash was priced at \$34 per bushel for 1,090 bushels. Electricity was priced at \$0.03/kWh. The profit from 0% solar is based on the profit from squash only. Source: Authors.

The yield of squash at which squash agrivoltaic become more profitable than squash alone was 981 bucket if 10% land is allocated for solar panels at all three heights, two arrays, \$0.02 electricity price and \$11 squash per bucket price (Fig 4) for all four regions in Alabama. The yield requirement dropped to 872 buckets at \$0.04 electricity price when keeping other factors constant in all four regions. The 872 bucket yield requirement was achieved for tracking solar mounted at 4.2 ft. height in black belt region at \$0.03 electricity price. In the southern region, the same yield requirement was achieved for tracking solar panels for all three heights at \$0.03 electricity price. The smallest yield required to achieve positive profit difference between agrivoltaic system and crop alone for squash was 218 bucket. This requirement was achieved in the black belt and southern Alabama for all three heights tracking solar panels when 20% land in allocated to solar panels, electricity price was \$0.04, and at \$11 per bucket. For the fixed agrivoltaic system with same system specifications and prices, the 436 buckets of squash were required to achieve greater profit from agrivoltaic system than crop alone in both regions. At \$0.03 electricity price all four regions achieved 218 bucket yield requirements when 35% of land is allocated for solar with tracking system for all heights. The yield requirement for squash agrivoltaic system to be more profitable than squash alone are plotted in figure 4 for various solar system configurations and energy and crop prices.

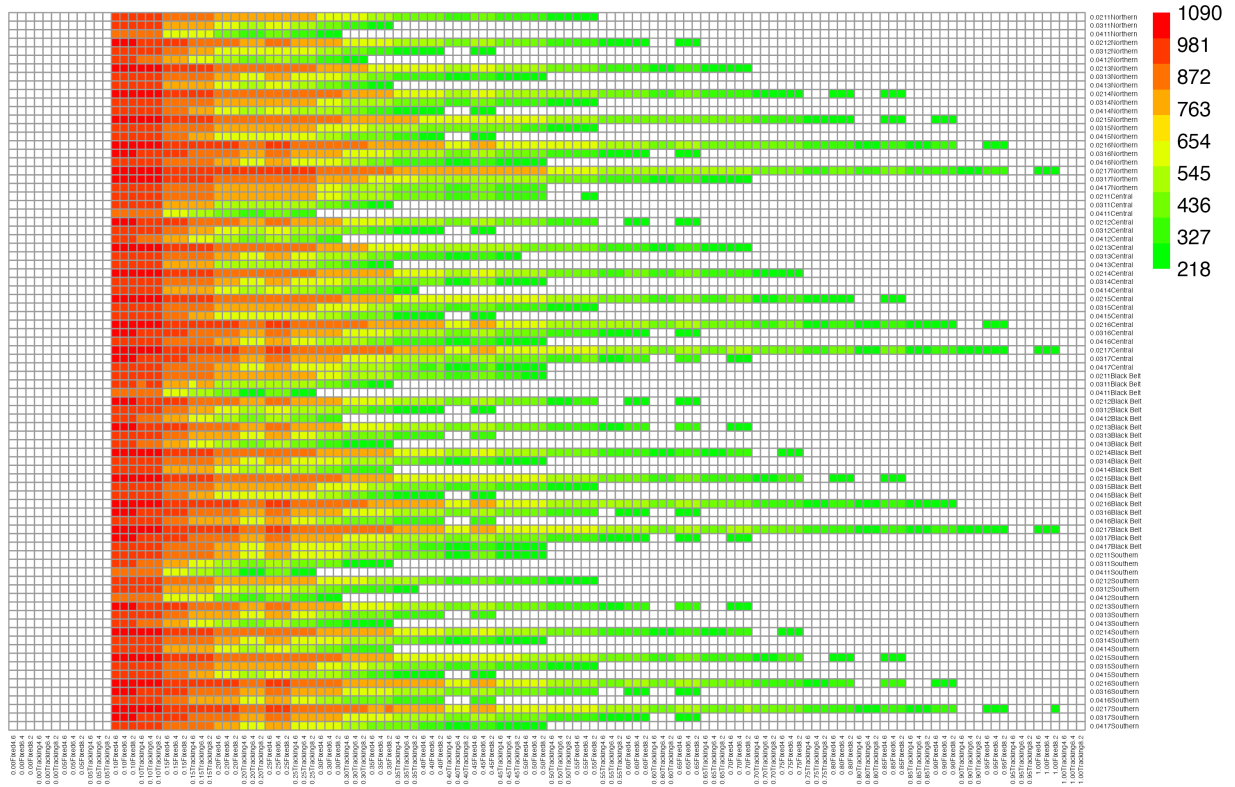


Figure 4: Summer squash yield (0.5bu buckets) at which the difference in the profit from squash agrivoltaic and the profit from squash alone is positive for the squash agrivoltaic system with the given specifications. The vertical axis consists of electricity price (\$/kWh), squash price, and regions of Alabama. The label on the first row, 0.0211Northern, consists of \$0.02/kWh electricity price, \$11 squash price, and Northern region of Alabama. There are three electricity prices, seven squash prices (\$11, \$12, \$13, \$14, \$15, \$16, and \$17), and four regions of Alabama. The horizontal axis consists of proportion of land covered by solar panels, solar panel array types, and solar panel ground clearance height (ft.). The label on the first column, 0.00Fixed4.6, consists of 0.00% land under solar panels, fixed tilt solar panels facing south, and solar panels mounted 4.6 ft. above the ground. White squares lack data because either the profit from squash agrivoltaic was less than that from squash alone (left side) or smallest yield was identified where the difference between squash agrivoltaic profit and squash profit alone is greater than zero (right side). Source: Authors.

Conclusion

We estimated revenue, cost, and profit of tomato, strawberry, and squash agrivoltaic systems for four regions of Alabama and compared with respective crop profits. We further estimated yield at which agrivoltaic systems become more profitable compared to respective crops alone under various configurations of solar system and crop and energy prices. We found that strawberry was more profitable followed by squash and tomato in the agrivoltaic systems. The profits were higher for solar tracking array compared to fixed array. Height did not affect the minimum yield required to achieve higher profit from agrivoltaic system compared to crop alone keeping other solar system configuration parameters and energy and crop prices constant in the given region of Alabama. The profit were higher in southern Alabama compared to northern Alabama due to higher energy production. Our findings suggest that between 5% to 10% of agricultural land must be allocated to solar for agrivoltaic to be profitable than the crop alone. We varied land allocated for solar by 5% during the simulation; modeling land allocation at the finer scale would provide more precise proportion of land allocation necessary to achieve equal or higher profit from agrivoltaic system than the crop alone. The higher price of electricity reduced the proportion of land necessary to achieve higher profit from agrivoltaic systems compared to crop alone. The land allocation requirement to meet the condition may also vary depending upon government policies, scale of operation, space for farm machinery, and cultural operations but we did not account for such factors in our work.

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