Collocating Specialty Crops and Solar panels in Alabama, Southeastern USA

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Introduction

Solar energy has become one of the most promising technologies to meet clean energy demand replacing fossil fuel and thus, vital to combat climate change. Agricultural land has greatest solar potential due to its flat terrain, long sun exposure duration, close to human settlement, well developed transportation network, and close to energy transmission grids compared to marginalized land making it the most suitable land for solar energy generation. As a result, solar energy production in agricultural land is expected to expand in the future, imposing competition for land between solar energy production and food production. Collocating solar panels with agricultural crops—agrivoltaic system—is an innovative approach to minimize the conflict between energy and food production.

The agrivoltaic system creates a unique condition where the trade-ff between land use for crops and solar panels is unavoidable. Producers face a land allocation problem as the land allocated for crop production decreases with the increase in land allocated for solar panels for given unit of land. This changes crop production and its profitability.

Tomato (Solanum lycopersicum L.) is one of the most widely cultivated specialty crops in the US with total economic contribution of $4.8 billion, 33,000 jobs, $400 million in federal tax, and $350 million in state and local taxes in 2016 [20]. However, tomato is mostly grown in the southwest (i.e., California and Arizona) and southeast (i.e., Florida, Georgia, Alabama, and South Carolina), where recent high spatial and temporal variability of regional weather conditions is impacting not only tomato but crop production in general. Particularly, the increases in daily air temperature and changes in rainfall pattern have been reported to impact tomato production in these regions as tomato is sensitive to drought: High temperature and water loss can decrease yields by 25% [21, 22]. For specialty crop production such as tomato, lettuce, and cucumber, experiments involving solar panels have been performed mostly in greenhouses that are partially shaded by solar panels [19]. To the best of our knowledge, there is only one peer-reviewed publication resulted from tomato based agrivoltaic system research conducted in Arizona, US [12], where the authors observed an increase in the yield of tomato grown under the photovoltaic system due to an improvement of photosynthesis probably caused by a reduction in temperature and protection provided by solar panels from the intense solar radiation of Arizona. The proposed project will be the first open field-based agrivoltaic experiment in the Southeastern US.

Squash is commercially produced throughout the US and it is available through the year [23]. The US grows $149 million-dollar worth squash in 2019 in 45,000 acres of agricultural land [24]. Southern states are one of the major producers of zucchini with its market expanded throughout the US. The production of squash increased by 15.2% between 2015 and 2020 throughout the US and top producing states increased production by 47.5%. Despite significant market in the US, the study of zucchini production is extremely limited; the proposed research on zucchini production in agrivoltaic system is the first study in the Southeastern US.

The current research in agrivoltaic system in the United States (US) is largely limited among four research groups [8]. Most of them are focused on arid, semi-arid, and temperate region such as Arizona, California, Illinois, and Michigan [8, 11, 12], [7]. The variation in environmental conditions are affected by the geographical location [8], site shading and orientation of plots [12]. Agrivoltaic system is also an appropriate form of clean energy in southeastern region due to its high solar potential [41] and low wind potential [42]. Moreover, the current focus of agrivoltaic research is mostly on row crops and livestock [8]. Our research is first attempt to propose agrivoltaic research in the southeastern US with the focus on specialty crops (tomato and squash in this study).

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 about the minimum crop yield required to achieve higher profit from agrivoltaic system than the respective crop alone at various electricity and crop prices and solar system configurations for four regions of Alabama.

Method

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 size 7.75 feet (ft.) by 3.5 ft. 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 6ft. The spacing between rows increases with the decrease in solar panel density. Plots with 0% solar densities have crops but lacks sola 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 annual revenue to get total profit from total solar energy production.

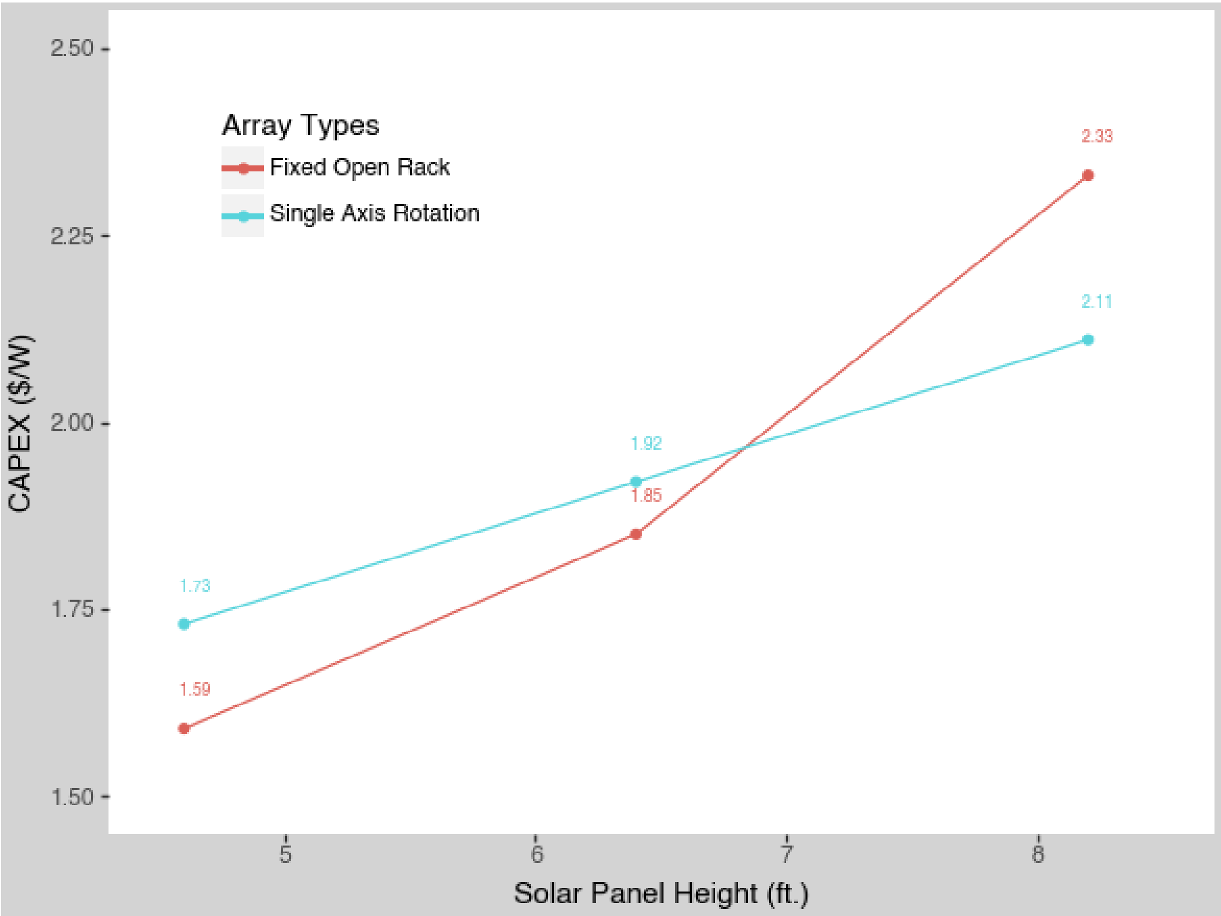

Figure 1: CAPEX for agrivoltaic systems with fixed open rack and single rotation axis array solar panel systems at 4.6 ft, 6.4 ft. and 8.2 ft. clearance height above the ground. The CAPEX were estimated following Horowitz et al. (2020) and the CAPEX for 6.4 ft. single axis rotation panel was predicted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

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 (Gomez-Casanovas et al., 2023). The shadow from solar panels could have positive effect of reducing heat stress (Othman et al., 2020), water stress (Omer et al., 2022), and protect crops (Willockx et al., 2022) but could reduce the yield (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 is equal to profit from crop alone and additional profit from agrivoltaic system above the crop profit at the given crop price. We estimated profits of tomato sold at $17 to $23 at $1 increment per 25 pound (lb) cartoon, 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) cartoon. We varied harvest labor and harvest container cost 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 is 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 separately for agrivoltaic systems with the three crops.

1. Results and Discussion

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 same 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.) →		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 ↓	Array ↓													
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 1224 bucket in black belt and southern Alabama for all three heights and two tracking system. The yield was equivalent to allocating uo 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.

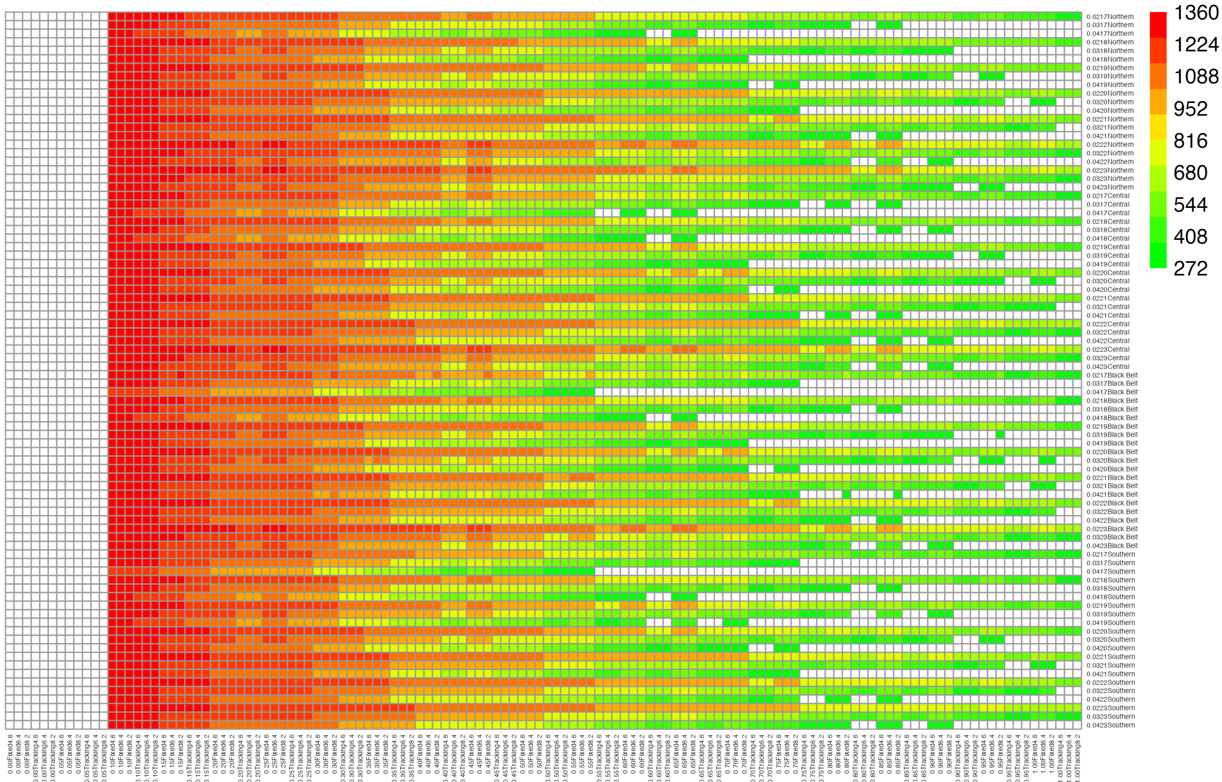

Figure 2: Tomato yield (25lb buckets) at which the difference in the profit from tomato agrivoltaic and the profit from tomato alone is positive for the tomato agrivoltaic system with the given specifications. The vertical axis consists of electricity price ($/kWh), tomato price, and regions of Alabama. 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.) →			**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 ↓	**Array ↓**													
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.

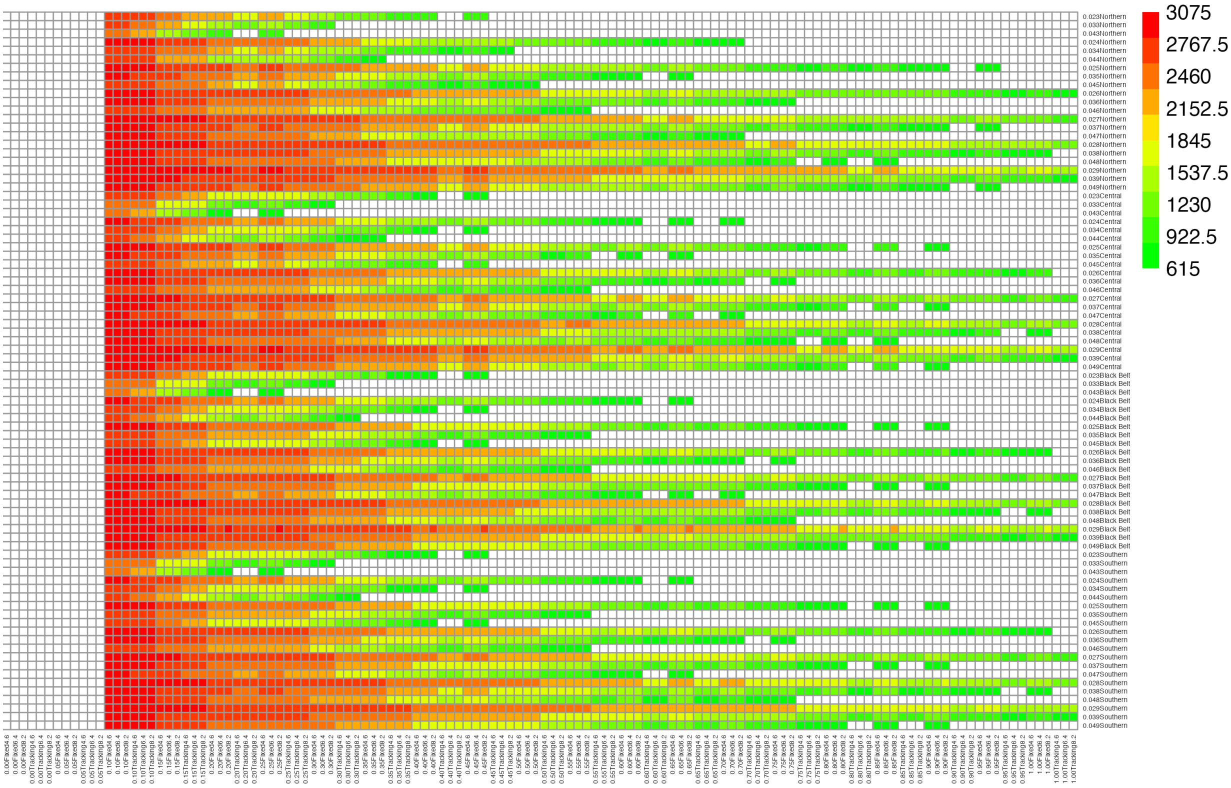

Figure 3: Strawberry yield (buckets) at which the difference in the profit from strawberry agrivoltaic and the profit from strawberry alone is positive for the strawberry agrivoltaic system with the given specifications. The vertical axis consists of electricity price (\$/kWh), strawberry price, and 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.) →		**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 ↓	**Array ↓**													
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.

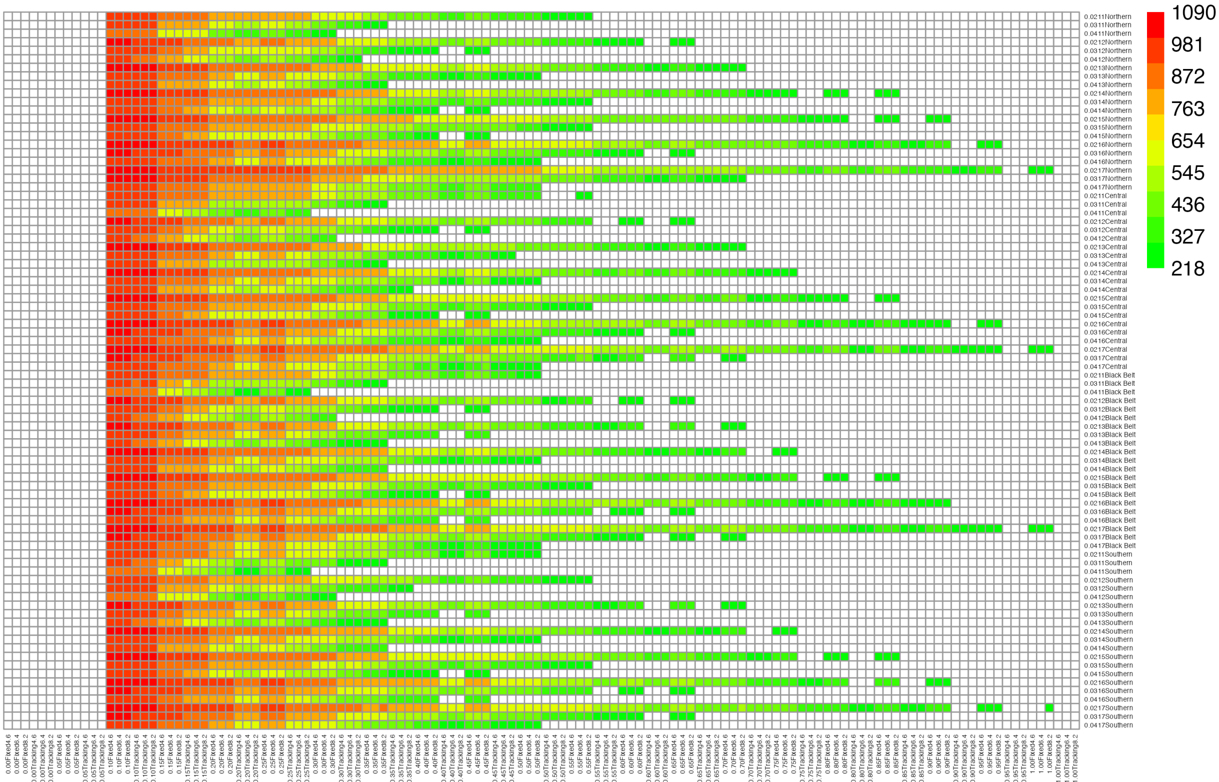

Figure 4: Summer squash yield (0.5bu buckets) at which the difference in the profit from squash agrivoltaic and the profit from squash alone is positive for the squash agrivoltaic system with the given specifications. The vertical axis consists of electricity price ($/kWh), squash price, and regions 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 yield requirement to achieve higher profit from agrivoltaic system compared to crop alone for the same solar system configuration, energy and crop prices 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 by 5% keeping other parameters constant for 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 would further reduce 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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