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Sources, Trends, and Drivers of U.S. Dairy Productivity and Efficiency

Eric Njuki

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Abstract

The U.S. dairy sector has undergone substantial structural change characterized by a shift to larger and fewer dairy operations, concentrated in relatively few States. This report measures and analyzes the dairy sector's productivity growth and efficiency and identifies proximate drivers and sources of this growth in the face of the structural change observed from 2000 to 2020. Results indicate that productivity growth in the dairy sector was widespread, albeit with considerable variations by herd-size class, region, and production type. Western and Southwestern States—Idaho, New Mexico, Arizona, and California—experienced the fastest productivity growth with annual rates between 3.52 and 4.40 percent. Meanwhile, Southern States—Kentucky, Georgia, Missouri, and Tennessee—were the slowest growing with annual rates ranging between 0.89 and 1.74 percent. Furthermore, productivity across the largest herd-size class with more than 1,000 milk cows grew at an annual rate of 2.99 percent while the smallest herd-size class with fewer than 100 milk cows grew at an annual rate of 0.63 percent. Finally, organic dairy operations grew at a much slower pace of 0.66 percent compared with their conventional counterparts that grew at an annual rate of 2.51 percent.

Keywords: U.S. dairy, productivity growth, total factor productivity, milk output per cow, technological progress, technical efficiency, scale-and-mix efficiency, environmental effects, conventional dairy, organic dairy

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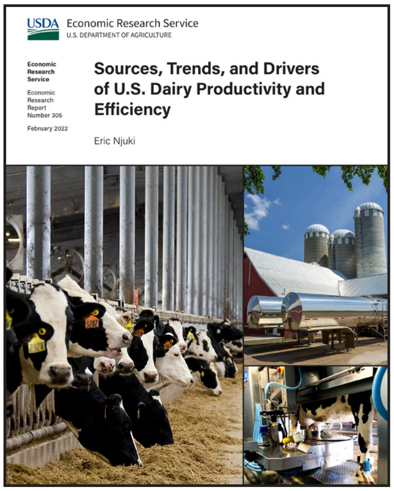
What Is the Issue?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Sources, Trends, and Drivers of U.S. Dairy Productivity and Efficiency

Eric Njuki

Global demand for milk and dairy products continues to rise, fueled by rapid population growth, rising household incomes, and favorable consumption patterns. Meanwhile, the United States plays a key role in world dairy markets having generated 11.6 percent of global milk output and 14 percent of global dairy exports in 2019 (United Nations Food and Agriculture Organization, 2020). Milk production for the domestic market continues to increase steadily. However, the net returns of production have consistently declined over the years because of production's rising costs, resulting in depressed profit margins for farmers. Furthermore, the national trend has been towards consolidation of dairy operations into larger and fewer farms. The majority of milk production in the United States is now concentrated in relatively few States located in the West, Southwest, Upper Midwest, and the Northeast regions (MacDonald et al., 2007; MacDonald et al., 2016; MacDonald et al., 2018; MacDonald et al., 2020). Despite continued growth in milk production, long-term climate trends and weather volatility may threaten this growth trajectory (Key and Sneering, 2014; Key et al., 2014).

This study builds upon previous USDA, Economic Research Service reports that focused on structural change and consolidation in the dairy sector by analyzing productivity growth, its sources, and current trends. In doing so, new insights are generated on critical questions, such as whether there are productivity gains in the dairy sector; how widespread these productivity gains/losses are across the sector; sources of productivity gains/losses; how environmental effects, that is temperature and precipitation, affect dairy productivity; the role of technological progress in productivity; and how organic dairy farming performs within the sector. In sum, this study seeks to understand the state of dairy production in the United States.

This study applied a model of productivity on dairy farms to generate measures of total factor productivity (TFP) to provide estimates of proximate drivers and components of TFP growth, including scale efficiency, technical efficiency, technological progress, and environmental components. In addition, the report compared and analyzed a single-factor productivity measure—milk output per cow (also referred to as milk yields).[1]

What Did the Study Find?

- From 2000 to 2020, milk output per cow increased at an annual rate of 1.53 percent nationally, with significant variations across States.
- From 2000 to 2016, total factor productivity (TFP) growth increased at an annual rate of 2.51 percent, albeit with variations across States and across herd-size class.
  - Technological progress was the primary driver behind TFP growth—growth associated with the discovery of new systems, processes, and methods of turning inputs into outputs. Examples include improved genetics, selective breeding, enhanced feed formulations, and advanced digital record keeping.
  - The pace of TFP growth was slowed by substantial declines in the rate of growth of scale-and-mix efficiency—a measure of the benefits obtained by changing the scale of operations and technical efficiency—which is a measure of how successful operators are at attaining their full potential.
  - Environmental effects caused by weather variability and anomalies had a negative impact on the overall welfare of cows or cow comfort.
  - The average total factor productivity growth between 2000-2016 for organic dairy operations was 0.66 percent compared with conventional dairy operations, which grew at an annual rate of 2.51 percent.

How Was the Study Conducted?

The study relied on data from several sources: farm-level data from the USDA Agricultural Resource Management Survey (ARMS); the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) Climate Group weather data for the years 2000, 2005, 2010, and 2016; State-level data based on USDA, National Agricultural Statistics Service (NASS) milk production reports from 2000 to 2020; the Census of Agriculture from 2002 to 2017; and data from the Dairy Herd Improvement Association (DHIA) from 1996 to 2019. The ARMS records on production practices as well as costs and returns were used to track milk output while controlling for inputs such as milk cows, labor, feed, intermediate materials (i.e., expenses on veterinary, electricity and fuel, fertilizer and pesticides), and capital.

The ARMS data were augmented with weather information from the PRISM Climate group to capture the production environment's characteristics. Subsequently, a total factor productivity (TFP) index covering the years 2000–2016 was measured and decomposed into various components, including scale-and-mix efficiency, technical efficiency, technological progress, and environmental effects to identify sources and drivers of productivity growth. Data from USDA, NASS milk production reports and the Census of Agriculture were used to construct measures of milk output per cow, providing additional information on structural and productivity patterns at the State levels from 2000 to 2020. Finally, data from the Dairy Herd Improvement Information Association (DHIA) provided additional information on milk output per cow by various herd-size classes and cow breeds from 1996 to 2019. The combination of these data sources provided a holistic picture on several aspects of productivity growth, including total factor productivity, and milk output per cow.

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[1] Other measures of single-factor productivity include milk per hectare, milk per unit of labor, and milk per feed unit.

Sources, Trends, and Drivers of U.S. Dairy Productivity and Efficiency

Introduction

The U.S. dairy sector plays a major role in the agricultural industry, supporting the livelihoods of farmers, their communities, as well as several industries across the value chain. In 2019, dairy production generated approximately $40.5 billion in cash receipts (USDA, ERS, 2020). The 2019 dairy cash receipts comprised the largest cash receipts of any other agricultural commodities in several States, including California, Wisconsin, Idaho, New York, Pennsylvania, Michigan, New Mexico, and Vermont. In addition, production continued to shift away from the traditional dairy States in the Northeast and towards the West and the Southwestern regions of the country, though Midwest and Northeast milk output shares stabilized over the last decade with production volumes growing (MacDonald et al., 2007; MacDonald et al., 2016; MacDonald et al., 2020). Yet, domestic market conditions have been such that dairy producers continue to face rising production costs, leading to depressed profit margins.

There has been substantial consolidation and structural change in the dairy sector marked by a shift in production from small to large dairy farms. In 2002, there were 73,725 farm operations with fewer than 100 milk cows, comprising 28.88 percent of the Nation's total herd (USDA, NASS, 2004). By 2017, this number had dropped to 40,548, comprising 12.69 percent of the Nation's herd (USDA, NASS, 2019). In 2002, the number of operations with more than 1,000 cows was 1,256–28.83 percent of the Nation's herd. By 2017, this number rose to 1,953 dairy operations, comprising 55.23 percent of the country's herd.

Concurrently, global demand for milk and other dairy products, such as cheese, butter, yogurt, whey products, and skim milk powder, continues to increase, primarily driven by rapid population growth, favorable consumption patterns of milk and dairy products, and rising household incomes—though this could change in the face of the global coronavirus (COVID-19) pandemic. In 1996, U.S. dairy exports comprised 3.6 percent of global exports. By 2019, this number rose to 14 percent of global exports (United Nations, Food and Agriculture Organization, 2020). This was due to increased trade resulting from a combination of factors that improved price competitiveness of U.S. products, including elimination of price support mechanisms domestically and abroad, the elimination of export barriers via the enactment of the World Trade Organization (WTO), and the introduction of free trade agreements that favor U.S. exports, and to a lesser extent, a moderate depreciation of the U.S. dollar relative to other currencies, thus making U.S. commodities relatively cheaper (Cessna et al., 2016; Davis and Cessna, 2020; Cessna and Teran, 2021). Despite the major role, the United States plays in world markets, the United States continues to face stiff global competition for world markets from other large dairy exporters, such as New Zealand, the European Union (specifically the following countries from the EU—Germany, France, Netherlands, Italy, Poland, and Ireland), Australia, the United Kingdom, among others.

Unfavorable weather and climate conditions in several regions where dairy operations are located have become commonplace. These are usually characterized by extreme temperatures—both hot and cold—flooding, droughts, and frequent intense storms. In turn, these environmental effects have negatively impacted dairy production by reducing the yield of feed grains (Schlenker and Roberts, 2009), lowering the quality and availability of pasture and forage, affecting the normal physiological functioning and reproductive health of dairy cows, and harboring the distribution and resiliency of parasites and pathogens affecting animal health (Wolfenson and Roth, 2018).

This report tracked the growth of milk output over time while controlling for inputs such as herd size, labor hours, feed, capital, intermediate materials (i.e., expenses on veterinary, electricity and fuel, fertilizer, and pesticides), and the production environments. In doing so, this study generates new insights and a better understanding of several aspects of productivity in the U.S. dairy sector. The focus of this report is on measuring and analyzing productivity, namely total factor productivity (TFP)—defined as the rate of growth of milk output relative to the rate of growth of aggregate inputs—and single-factor productivity or milk output per cow (i.e., milk yields).[2]

This report builds upon previous studies that examined various aspects of the U.S. dairy sector, such as consolidation, structural adjustments, and cost of production (e.g., MacDonald et al., 2020; MacDonald et al., 2018; MacDonald et al., 2016). Some additional research questions include investigating the sources of productivity, evaluating production efficiency and its role in consolidation and structural adjustments, the effect of weather and climate on dairy productivity, and investigating how organic dairy farming has performed.

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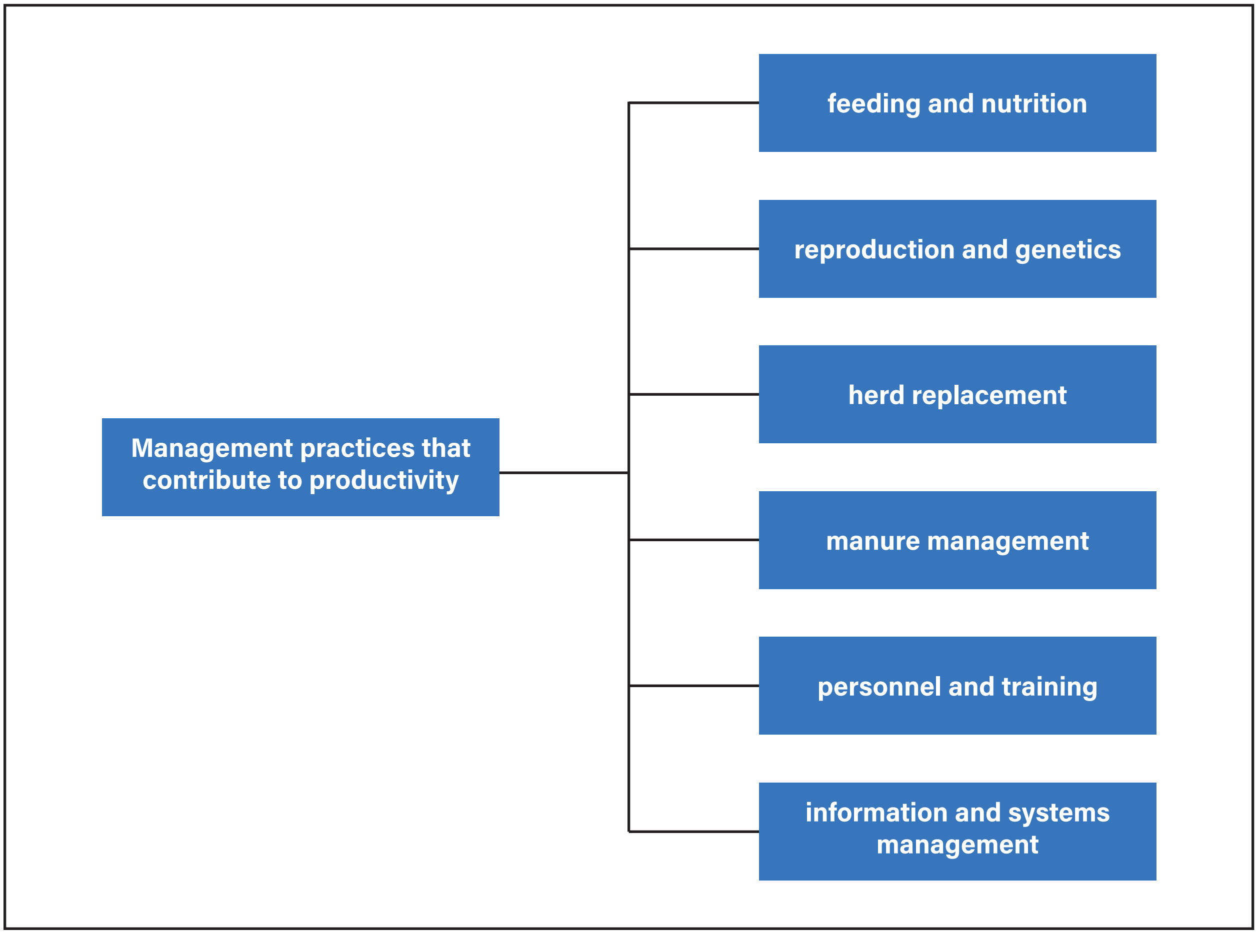
[2] Other measures of single-factor productivity include milk per hectare, milk per unit of labor, and milk per feed unit.

Management Practices and How They Translate to Productivity and Efficiency

Like any other commercial enterprises, dairy operations thrive on sound business practices. The successful dairy operation is proficient at harnessing various inputs to produce at full potential. Producers can achieve productivity growth and efficiency by pursuing targeted, deliberate, and purposeful production practices aimed at key sources of productivity, namely: technological progress, technical efficiency, and scale-and-mix efficiency. Here, technological progress refers to productivity gains associated with innovations and the discovery of new processes, systems, and methods of production; scale-and-mix efficiency refers to gains associated with economies of scale or the benefits obtained from changing the scale of operations; and technical efficiency which refers to the managers' ability to maximize output given the inputs at their disposal. Other factors, such as environmental effects, are associated with long-term climate trends and weather volatility—these are entirely random, though dairy producers can mitigate their effects by modifying the diet to maintain feed intake, regulating temperatures by installing cooling and heating systems, and building better barns with adequate airflow and ventilation to decrease moisture and humidity while accommodating equipment such as feeding and milking systems.

A typical U.S. dairy producer makes decisions on how to manage these practices in day-to-day operations. Figure 1 lists several key management practices, including feeding and nutrition, reproduction and genetics, herd replacement, manure management, personnel and training, and information systems management. These practices can contribute to productive, efficient, and profitable dairy establishments while enhancing the overall well-being of the cow.

Figure 1
Management practices in dairy farming that contribute to productivity and efficiency



Source: USDA, Economic Research Service.

Feeding and Nutrition

Feeding and nutritional management is the use of feeding systems to deliver nutrients to livestock. The types of feeding systems largely depend on herd size. They include total mixed rations (TMR) feeding systems, component feeding systems, and management-intensive feeding systems.

Total mixed rations feeding systems generally involve combining feeds formulated to include specific nutrient content. They usually combine forages and pasture, grains, proteins, vitamins, and minerals. TMR can to be an efficient and labor-saving approach for delivering the desired level of nutrients (Dinsmore, 2015).

Component feeding is a nutrient management approach where livestock are provided grain and forage separately. This is typical in smaller herd sizes where cows are maintained in stalls and barns. This form of nutrient management allows for a more targeted and individualized feeding approach that aids in conserving scarce nutritional resources while avoiding waste. This approach typically targets reproductive status—heifer, lactating, and dry cows—and/or performance status—high, medium, or low production cows (Erickson and Kalscheur, 2020).

Finally, a management-intensive dairy feeding system is a common approach that emphasizes low costs and relies on open pasture and forage. However, because of pasture and forage's seasonality, operators may practice rotational grazing or provide supplemental nutrition in the form of concentrate and corn silage.

Reproduction and Genetics

Reproductive management is the breeding and genetic component of dairy cattle management. Its origins reflect aspects of technological progress that can build productive and resilient herds suitable for a given environment. Optimal reproductive management can generate highly productive cows while increasing their longevity and productive lifespan. Breeding methods include natural service and artificial insemination. Artificial insemination generally implies purchasing semen from a provider, while natural service implies owning or renting bulls. By 2014, natural service was used exclusively by 10.7 percent of operations while 43.7 percent of dairy operations used artificial insemination exclusively (USDA, Animal and Plant Health Inspection Service, 2018).

Considerable skill and knowledge goes into reproductive management—selecting genetically superior sires, timing of artificial insemination in order to detect estrus (the narrow window of optimal fertility), and the proper handling and storage of the semen (Dinsmore, 2015). An emerging practice, following years of research, is the use of sexed semen through in-vivo and in-vitro embryo production. The use of sexed semen among heifers enables producers to obtain offspring of a predetermined sex as well as expedite the genetic progress and improvement of the heifer stock (Holden and Butler 2018). Furthermore, for milk producers who are interested in more heifers than bull calves, the use of sexed semen allows producers to take advantage of gender value difference, by building and maintaining a herd size of milk-producing cows only. These factors can contribute to a highly productive stock.

Herd Replacement

In addition to breeding and genetics, the timing of rearing heifers and replacing older cows goes a long way in building highly productive herds. This is in addition to maintaining the appropriate stocking rate and building the optimal scale of production. One approach involves accelerating the growth of heifers by reducing the age at first calving—the age at which a heifer has her first calf. There are several advantages to this, such as decreased maintenance costs, higher cumulative milk production, and shorter generational intervals. However, these advantages have to be weighed against diminished conception rates, lower milk production per lactation, reduced longevity of the herd, and higher costs because of increased nutrient density (Krápalková et al., 2014; Hoffman et al., 1996).

Manure Management

Manure management involves the production, collection, transfer, storage, and disposal of manure. A typical lactating cow weighs 960–1,760 pounds and can generate an average of 150 pounds per day of manure and urine (American Society of Agricultural and Biological Engineers, 2005).[3] [4] Manure management is one of the key elements of day-to-day management of any dairy operation. The type of manure management system is determined by various factors including the herd size, the type of housing, the location, and existing laws and ordinances.

Unsanitary conditions, including contaminated milking equipment and improper handling of manure, could contribute to the festering of disease-causing pathogens and cause opportunistic infections in livestock, such as mastitis. According to the National Animal Health Monitoring System (USDA, APHIS, 2016), 99.7 percent of dairy operations reported at least one incident of clinical mastitis. Although antimicrobials were administered in most cases, incidents of mastitis resulted in increased costs because of treatment and low productivity in the affected livestock. Although almost 75 percent of cows recovered, 25 percent had to be prematurely culled from the herd. Unsanitary conditions increase the prevalence of morbidity in dairy cows resulting in decreased milk yields, lower milkfat content, delayed conception, and—ultimately—higher incidences of involuntary culling. Thus, manure management directly affects the productivity of the dairy operation.

Manure can be a valuable resource that can be composted and used to fertilize pastures and cropland, thus lowering the cost of production by minimizing the use of synthetic chemicals and fertilizers (Adhikari et al., 2005; Paudel et al., 2009). Similarly, the use of equipment such as anaerobic digesters may convert cow manure into renewable energy that can be used to power a farm's heating and cooling equipment or sold to the energy grid. In sum, inappropriate and poorly managed manure systems pose significant environmental problems, including surface and ground water pollution via leaching and nutrient runoff, soil pollution through excess nitrogen loading, air pollution through odors, and the generation of methane and nitrogen, two greenhouse gases with considerable global warming potential.

Personnel and Training

Almost all dairy operations rely on some form of labor. Dairy operations with smaller herd sizes are more likely to rely on family labor than larger dairy enterprises. Whether hired or family labor is used, there are common labor practices that can make any dairy operation successful. Personnel training is one of them. Employees must be familiar with operations on the dairy enterprise, including milking, animal handling and movement, feeding cows, personnel safety, surgical procedures (e.g., dehorning and castration of dairy steer calves), calf raising and feeding, as well as the proper handling of machinery and equipment (USDA, APHIS, 2018). A skilled labor force on the dairy farm will unmistakably translate into higher labor productivity that—in turn—contributes to overall dairy productivity.

Information Systems Management

The proper storing, processing, and maintaining of dairy operation information so it's accessible and measurable can transform dairy operations into highly productive and profitable enterprises. The digitization of dairy farm records can improve information sharing between stakeholders while generating substantial cost-savings. Advanced technologies, though widely available, have not been uniformly adopted. Limitations include high adjustment costs—such as the costs of installation, training, and maintenance.

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[3] The American Society of Agricultural and Biological Engineers D384.2 on manure production and characteristics was first published in 2005. These figures were subsequently reaffirmed in November 2019.

[4] Approximately 12 percent of this is solid waste and the rest is moisture.

Examples of advanced technologies include biosensors equipped with micro-processors and radio frequency identification (RFID) that enable the monitoring of nutrient intake, milk production and content for individual cows, detection of estrus, as well as the general well-being of the cow. Other advanced technologies include robotic milking machines that have enabled improvements in milking frequency and timing to raise milk yields, and unmanned aerial vehicles or drones that can map the location of specific herds as well as determine the location of suitable pasture for grazing. An in-depth analysis of the data is possible when these are integrated with components of artificial intelligence, which—in turn—can improve the decision-making process in dairy operations.

Analyzing Milk Output per Cow

Estimates of milk per cow or milk yields were easy to generate and provided meaningful information on a key productivity aspect.[5] This study developed information on milk output per cow using data from three main sources:

- the Council on Dairy Cattle Breeding (CDCB), which collects information from regional and State Dairy Herd Improvement Associations (DHIA). The CDCB took over reporting from the USDA, Agricultural Research Service (ARS) animal genomics and improvement laboratory;
- the USDA, National Agricultural Statistics Service (NASS), which generates annual milk production reports and the Census of Agriculture; and
- the Agricultural Resource Management Survey (ARMS), which comprises farm-level surveys conducted by the USDA, Economic Research Service (ERS) in conjunction with USDA, NASS.

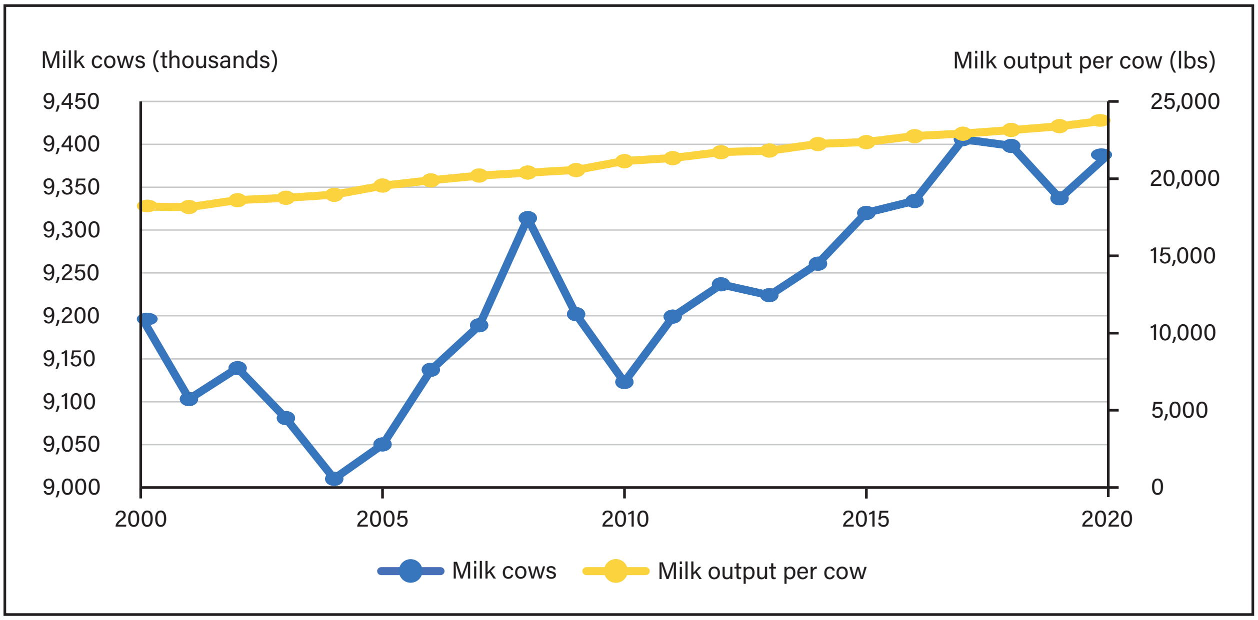
The CDCB reporting is based on and assumes 305 milking days a year, so CDCB reporting only includes lactating cows. USDA, NASS estimates are based on 365 days, and thus include both dry cows and lactating cows. ARMS estimates are calculated as total annual milk production divided by the number of lactating and dry cows on the farm at the end of the year.

Trends in Milk Output per Cow

Figure 2 illustrates milk output per cow juxtaposed with number of milk cows. These numbers were generated using estimates obtained from USDA, NASS milk production report. Milk per cow increased at an average annual growth rate of 1.53 percent, from 18,197 pounds per cow in 2000 to a high of 23,777 pounds per cow in 2020. Meanwhile, the size of the national herd increased from 9,199,000 in 2000 to 9,388,000 in 2020, an annual growth rate of only 0.10 percent.

Figure 2

Tracking changes in milk yields and milk cows across the United States, 2000–2020



Note: Average milk output per cow juxtaposed against the number of milk cows in the United States from 2000 to 2020.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, Milk Production report.

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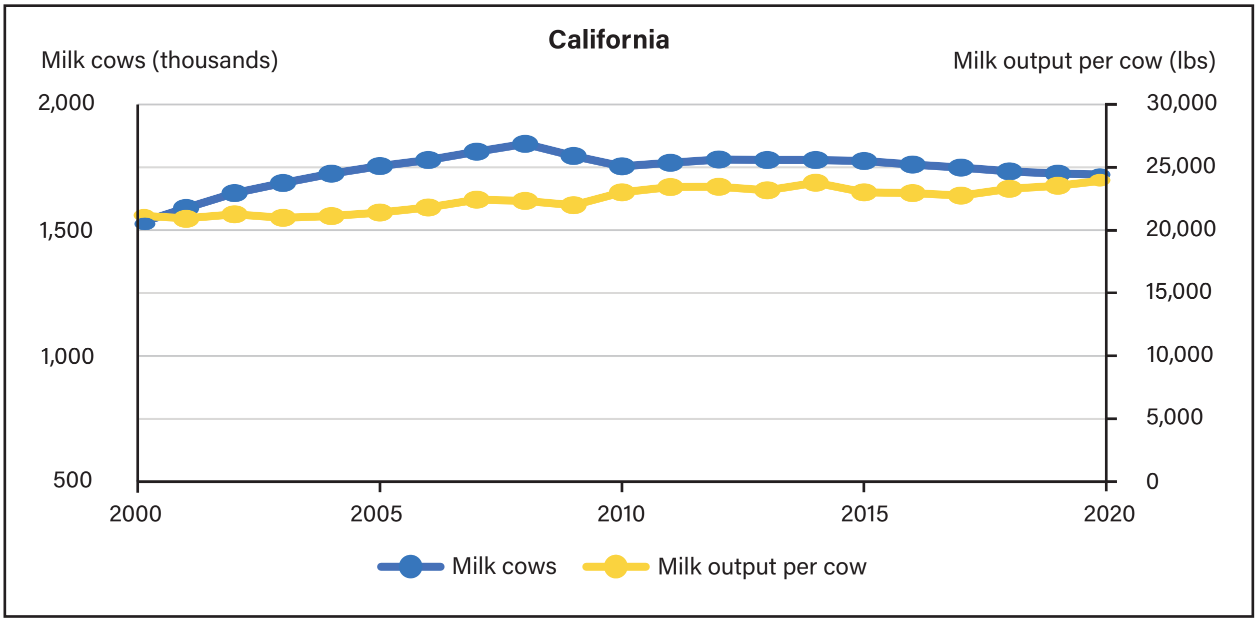
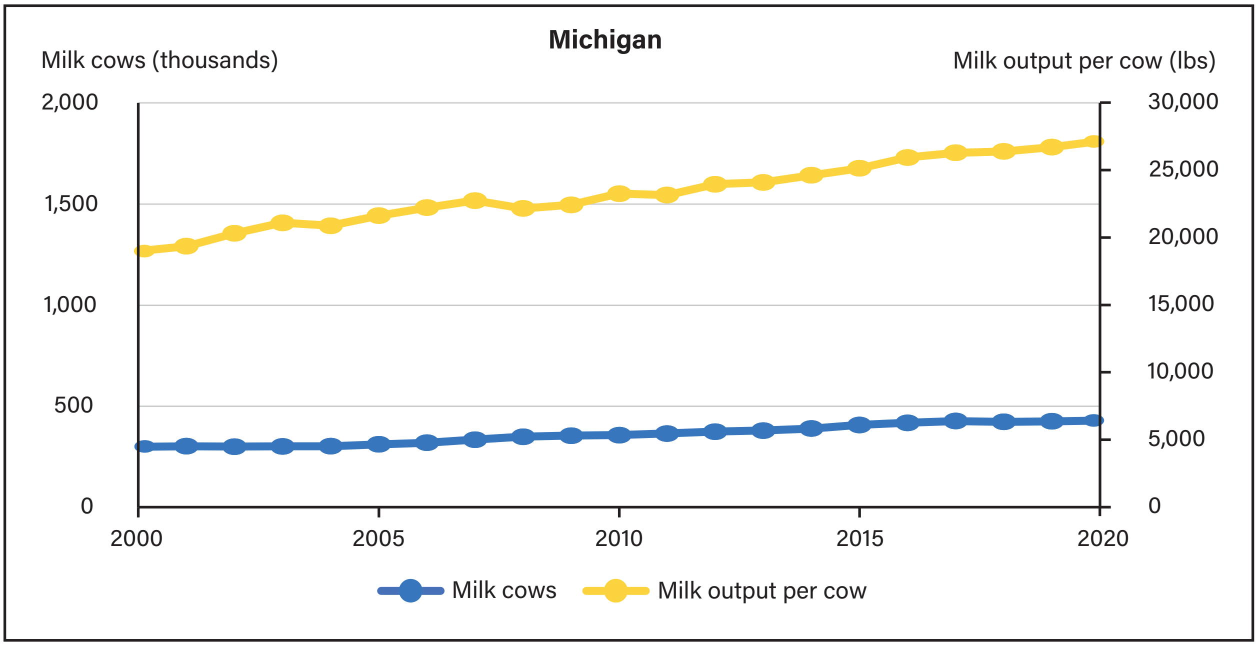
[5] Examples of other commonly used single-factor productivity measures include crop yields and labor productivity.

Similarly, the panel in figure 3 provides a snapshot of milk yields across various select States: California, Michigan, Vermont, and Idaho. These States represent regions characterized by various production practices and environments. California is the largest milk producer, Vermont is a traditional milk producer, Idaho is a rapidly growing milk producer—and the third largest dairy producing State in the country—and Michigan, a traditional Midwestern dairy State, experienced a surge in big dairy farms in recent years and reported the highest milk yields in 2019. This report observed that the annual growth rate of milk yields increased steadily over the years—by 0.67 percent in California, 1.20 percent in Vermont, 1.04 percent in Idaho, and 2.14 percent in Michigan.

Figure 3

Tracking changes in milk yields and milk cows across select States, 2000–2020





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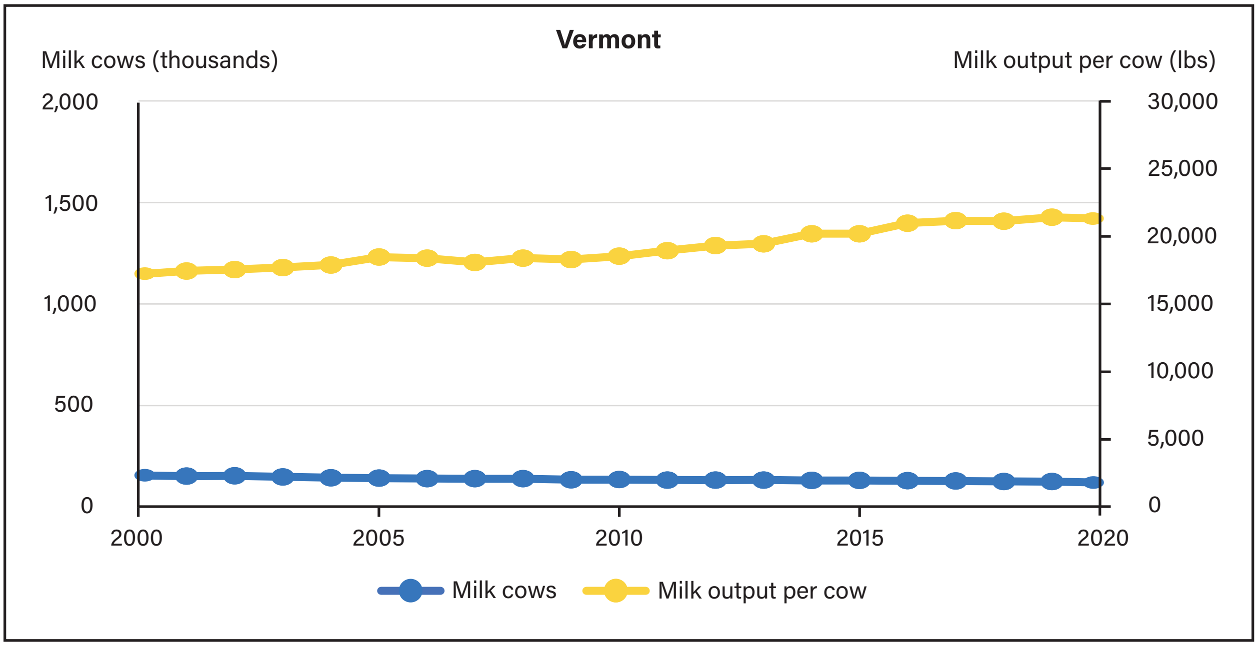
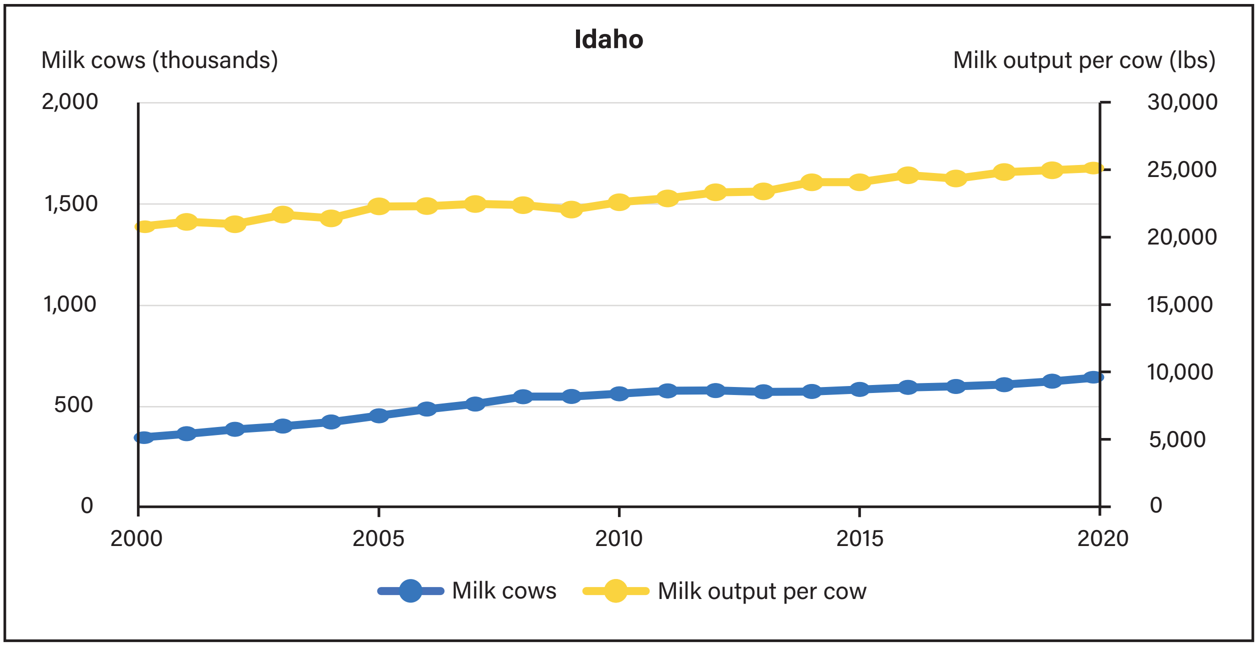




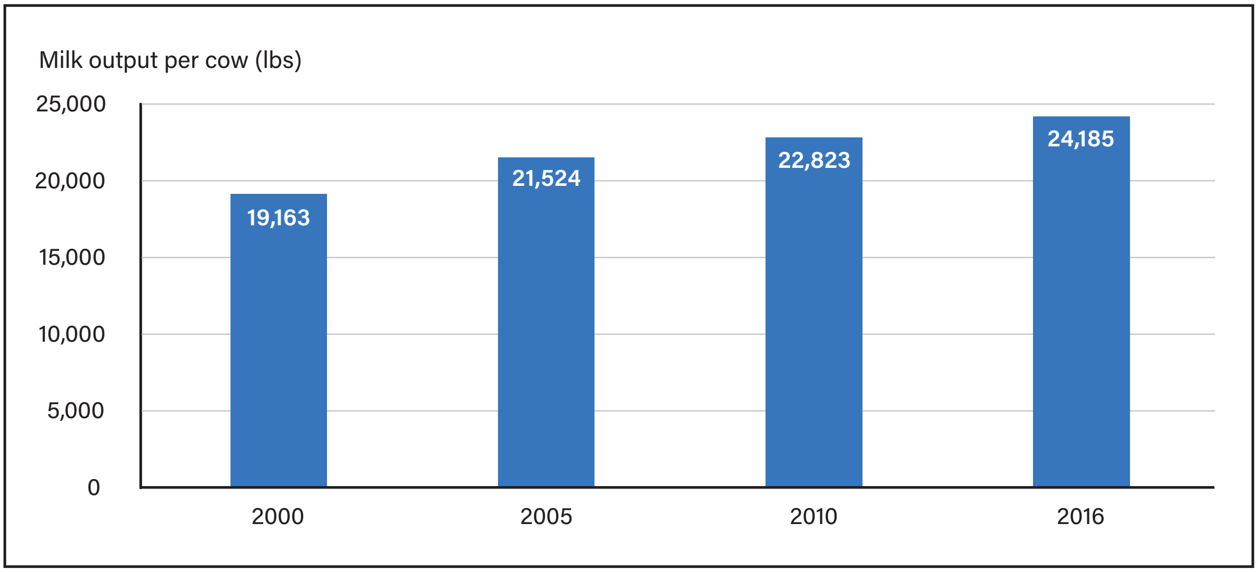
Note: Average milk output per cow juxtaposed against number of milk cows from 2000 to 2020 across four States: California, Michigan, Vermont, and Idaho.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, Milk Production report.

Figure 4 reveals a similar trend. Using ARMS data, researchers have noted milk yields have steadily increased over the years, beginning at 19,163 pounds per cow in 2000 and peaking at 24,185 pounds per cow in 2016, at an annual rate of 1.15 percent.

Figure 4

Milk output per cow, 2000–2016



Note: Average milk output per cow across four survey years: 2000, 2005, 2010, and 2016.

Source: USDA, Economic Research Service using 2000, 2005, 2010, and 2016 USDA, Economic Research Service and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data.

Figure 5 illustrates milk yields by breed for select years from 1996 to 2019 using data generated by the Dairy Herd Improvement Association (DHIA). The highlighted breeds include Brown Swiss, Jerseys, Holsteins, Mixed Breeds, and others breeds that comprise Ayrshires, Guernsey, and Milking Shorthorns. Holsteins consistently produced the highest milk yields while averaging growth rates of approximately 1.41 percent per year from 1996 to 2019. It is noteworthy that in 2014, Holsteins represented 86 percent of milk cows in the United States from a high of 93 percent in 2002.[6] This reduction in Holstein milk cows may be attributed to crossbreeding as dairy producers sought to selectively breed for specific cow traits, and the result was a shift from pure Holstein breeds to mixed breeds. The next highest milk yields were generated by Mixed Breeds,[7] Jerseys, and Brown Swiss averaging growth rates of 1.78 percent, 1.39 percent, and 1.02 percent, respectively. There was hardly any growth in milk yields from the other breeds—Ayrshire, Guernsey, and Milking Shorthorn varieties.

Dairy producers raise different breeds for various reasons: production volumes, milk composition including fat content, feed and maintenance costs, acclimatization to various geographic conditions, as well as legacy reasons based on the cow infrastructure in place. For example, Holsteins are notable for their high milk volumes, Jerseys produce milk with high butterfat content ideal for making butter and cheese, and Brown Swiss produce milk with high protein-to-fat ratio ideal for making cheese. Jerseys are also adaptable to a wide range of climatic and geographic conditions and are typically smaller in size, which means lower average feeding costs. Over the years, advancements in genetics have enabled crossbreeding to selectively breed specific traits from each breed. As shown in figure 5, the number of Mixed Breeds has been increasing over the years.

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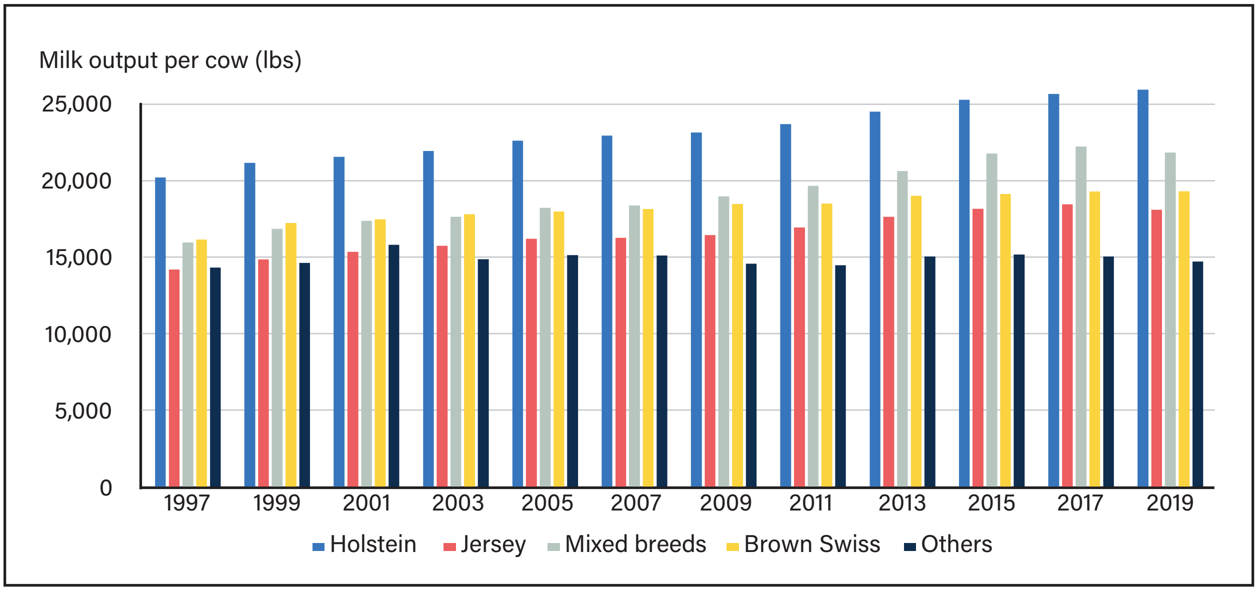
[6] According to the 2014 National Animal Health Monitoring System issued by the USDA, Animal and Plant Health Inspection Service. Available online.

[7] Mixed breeds are popular among milk producers because of their high component milk, smaller body and frame size that allow continued use of existing stalls and parlors, and gestational wellness (Guinan et al., 2019).

Figure 5

Milk yields by breed using information from DHIA, 1997–2019



Notes: Milk yields by breed for select years: 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013, 2015, 2017, and 2019. Breeds included are Holstein, Jersey, Mixed breeds, Brown Swiss, and Other breeds—which comprise Milking Shorthorns, Ayrshire, and Guernsey.

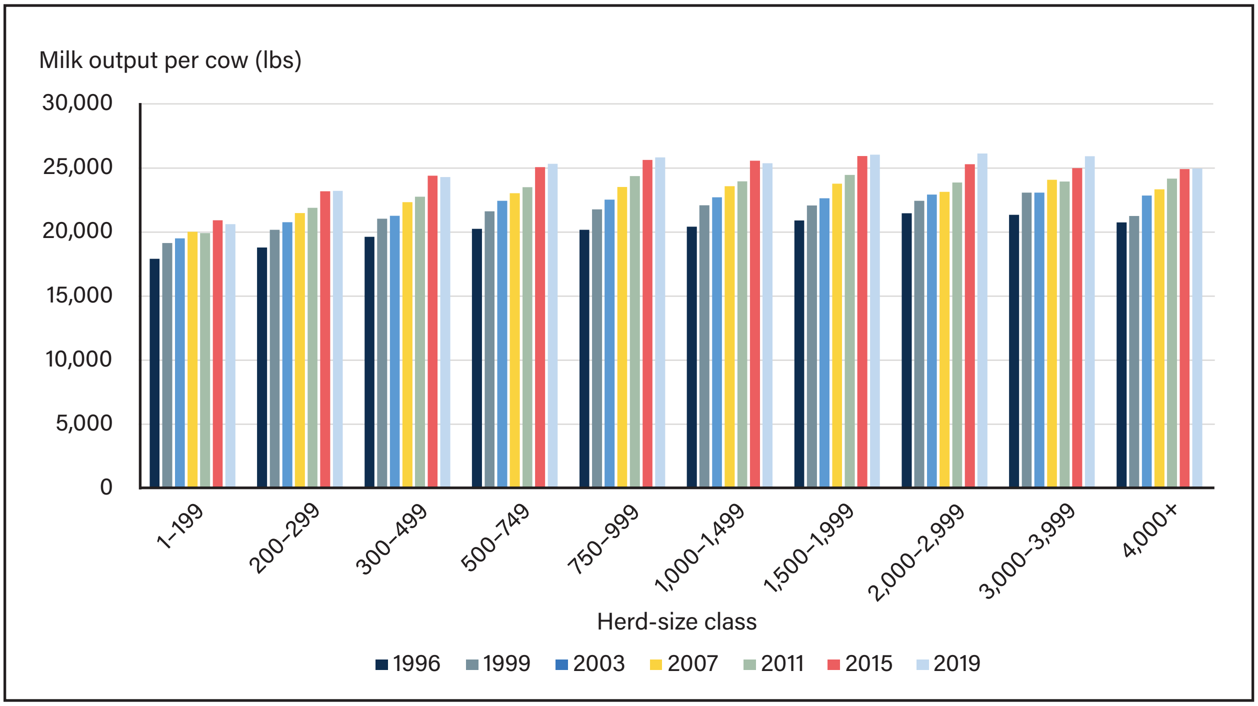
Source: USDA, Economic Research Service using Council on Dairy Cattle Breeding, Dairy Herd Improvement Association (DHIA) data.

Herd Size Matters for Milk Yields

Figure 6 illustrates milk yields by herd size for select years between 1996 and 2019 using DHIA information. Each cluster represents a particular herd size, ranging from dairy operations with fewer than 200 milk cows to those with more than 4,000 milk cows. We observe steadily rising milk yields up to herd sizes with 2,000–2,999 milk cows. Thereafter, there is a modest decline in milk yields in dairy operations with more than 4,000 milk cows. The fastest growth in milk yields was 1.16 percent per year by dairy operations with 750–999 milk cows. Meanwhile, the largest dairy operations with 3,000–3,999 and with more than 4,000 milk cows reported annual growth rates in milk yields of 0.89 percent and 0.84 percent, respectively. Finally, the slowest growth in milk output per cow was 0.59 percent per year reported by dairy operations with fewer than 200 milk cows. Figure 6 illustrates the shift over the years to larger herds resulting in higher milk yields, providing an important indicator of the optimal scale of dairy operations in the United States.

Figure 6

Milk yields by herd size using information from DHIA, 1996–2019



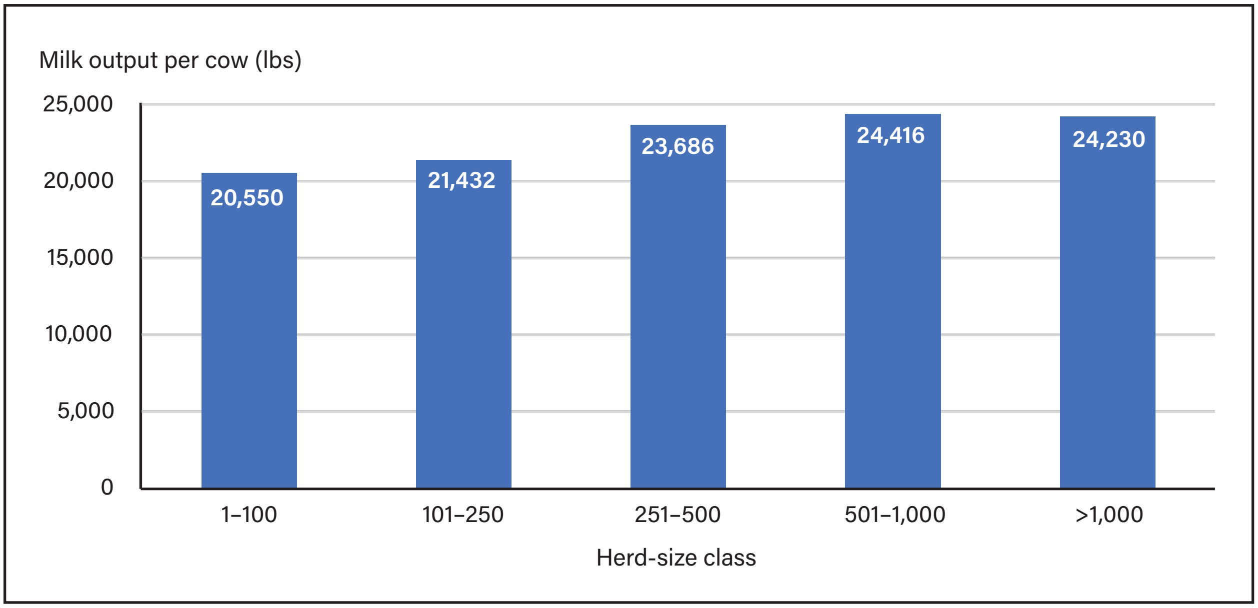
Notes: DHIA=Dairy Herd Improvement Association. Milk yields by herd-size class across select years: 1996, 1999, 2003, 2007, 2011, 2015, and 2019.

Source: USDA, Economic Research Service using Council on Dairy Cattle Breeding, Dairy Herd Improvement Association data.

A similar trend in milk yield by herd size is revealed when using the ARMS data. Figure 7 shows milk yields peaking at herd sizes with 501–999 milk cows, and thereafter, a modest decline for the largest herd size with more than 1,000 milk cows.

Figure 7

Average milk yields for conventional dairy operations by herd size using information from the ARMS, 2000–2016



Notes: ARMS=Agricultural Resource Management Survey. Average milk yields across five herd-size classes, 1–100, 101–250, 251–500, 501–1,000, and 1,000+.

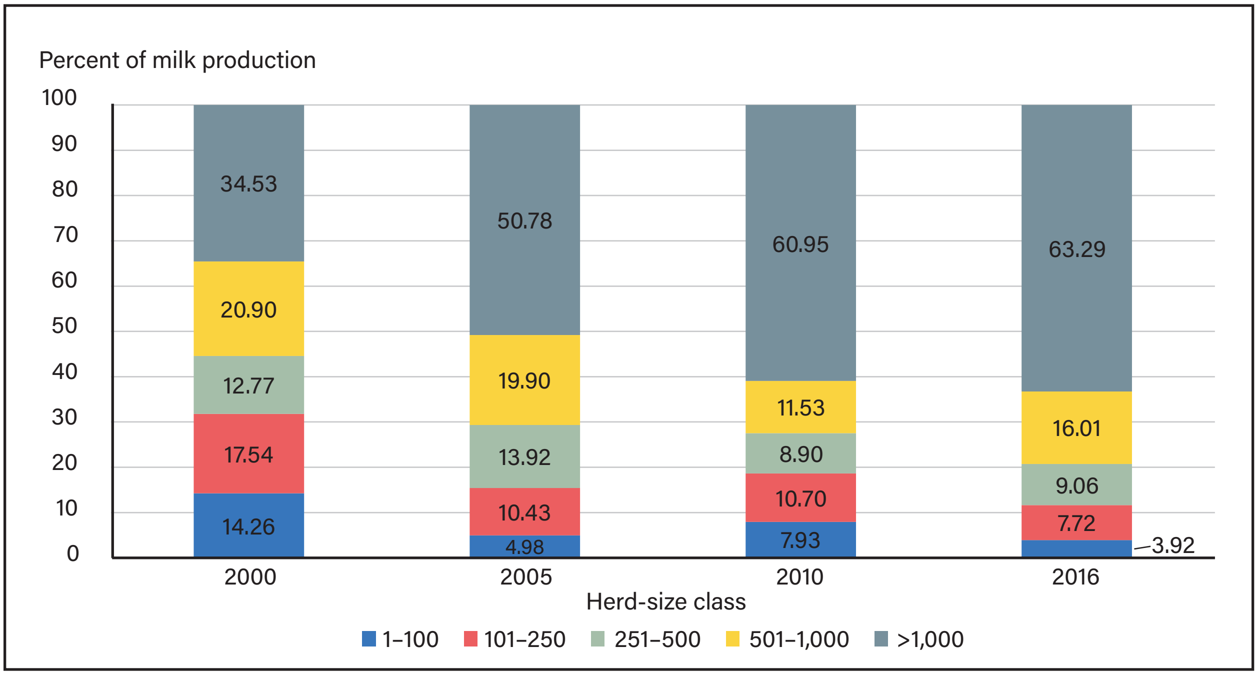
Source: USDA, Economic Research Service using USDA, Economic Research Service, and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data.

Milk Production Has Gradually Shifted to Larger Herd Sizes

Figure 8 shows a gradual shift in milk production over the years to larger herd sizes. In 2000, 14.26 percent of milk production was generated by operations with fewer than 100 milk cows, while 34.53 percent of milk production was by dairy operations with more than 1,000 milk cows. In 2016, only 3.92 percent of milk production was generated by dairy operations with fewer than 100 milk cows. Meanwhile, 63.29 percent of milk production came from dairy operations with herd sizes greater than 1,000 milk cows. In sum, the data provide evidence of a steady increase in milk yields by herd size as well as a shift in milk production to larger dairy operations.

Figure 8

Percentage of milk production for conventional dairy operations by herd size, 2000–2016



Source: USDA, Economic Research Service using USDA, Economic Research Service, and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data.

Total Factor Productivity Growth in the U.S. Dairy Sector

As noted in the introduction, total factor productivity (TFP) change measures the rate of growth in aggregate output relative to the rate of growth in aggregate inputs. Measuring TFP involves computing TFP indexes and then evaluating and analyzing changes in these indexes.[8] The sources of productivity growth are identified by subsequently decomposing a TFP index as shown in figure 9.

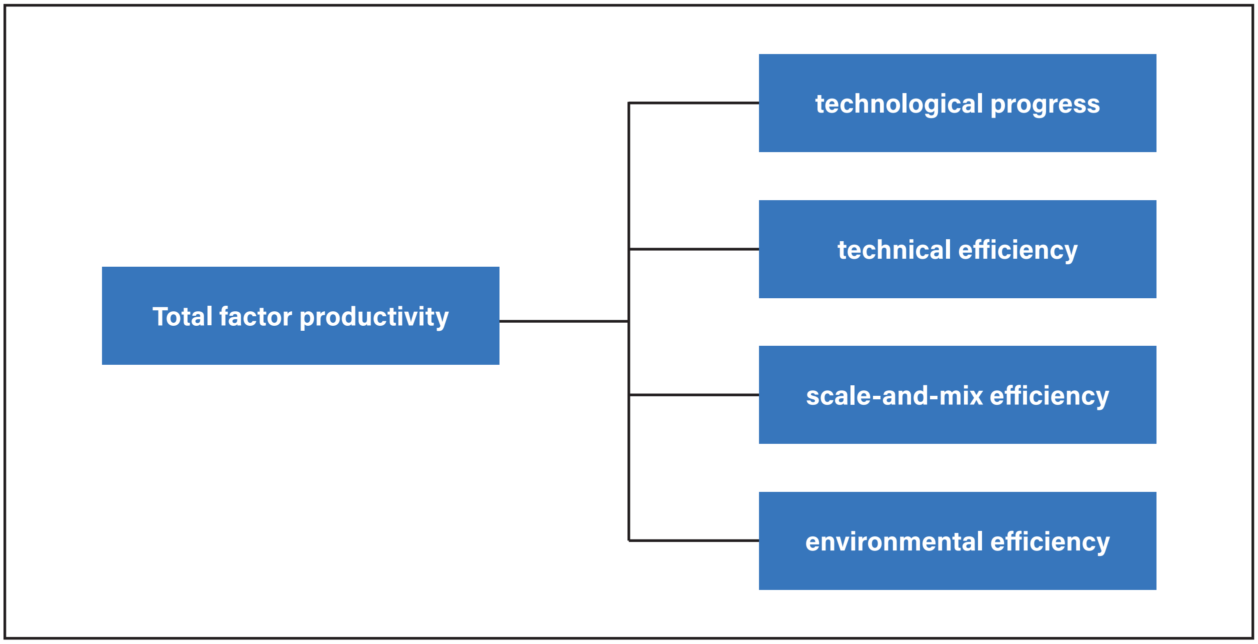
These sources include:

- technological progress—innovation and measures productivity gains associated with the discovery of new knowledge, processes, and systems that convert inputs into outputs such as advanced equipment and machinery, and genetic enhancement in livestock among others;
- scale-and-mix efficiency—measures productivity gains due to economies of scale and substitution or benefits associated with producing at the optimal scale;
- technical efficiency—measures how successful managers are at combining various inputs at their disposal to maximize output; and
- environmental effects—captures productivity gains associated with the physical characteristics of the production environment such as rainfall, temperature, soil quality, terrain, wind-speed, number of frost-free days, and how these affect production.

Decomposing TFP enables more targeted intervention.

Figure 9

Total factor productivity and its components



Source: USDA, Economic Research Service

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[8] Total factor productivity (TFP) is the ratio of aggregate outputs relative to aggregate inputs. A TFP index is any variable that compares the TFP of a farm *i* in period *t* relative to the TFP of a firm *k* in period *s* (O'Donnell, 2018).

The Role of Technological Progress in Enhancing Dairy Productivity

In milk production, technological progress can be classified into physical and biological components. The physical component of technological progress comprises innovations in feed handling equipment to deliver nutrients to animals more efficiently. Others include advanced digital record keeping; high-speed communication; advanced manure removal equipment; and structures that improve cow comfort and enable the efficient collection, transportation, and disposal of manure. And finally, milk quality measuring and monitoring equipment to gauge somatic cell counts[9] to determine viable aerobic bacteria in raw milk; robotics, and voluntary milking systems; and unmanned aerial vehicles or drones to monitor and locate individual cows as well as scan cropland and pasture (Halachmi et al., 2019; Foldager et al., 2020; Miller et al., 2020).

The biological components include improved genetics, breeding, growth hormones, the use of sexed semen to enable selective breeding, and improved feed formulation to deliver optimal feed nutrients targeted to the cow's lifecycle. Examples of biological innovations include research on genomic selection on U.S. Holstein breeds that led to rapid genetic improvement in fertility, longevity, and overall health of the cow (Garćia-Ruiz et al., 2016). When coupled with breeding values that emphasize phenotype, improved genetic selection can be directed towards developing traits associated with resilience to environmental factors such as heat tolerance (Cole et al., 2020).

Technical Efficiency in Dairy Production

As mentioned above, technical efficiency measures how successful managers are at combining various inputs and using them to their full potential in order to maximize milk production. The various inputs available to a dairy operation—such as the number of milk cows, equipment and machinery, homegrown and purchased feed, labor, and intermediate materials such as chemicals, fertilizers, veterinary services, and more—constitute a dairy operation's output potential. How well a dairy operator combines these inputs will determine how close output is to a farm's full potential. Thus, technical efficiency is usually associated with managerial performance. More proficient managers—through an effective combination of skill, experience, education, and learning-by-doing—are good at maximizing their output potential. Less adept managers are unlikely to produce at their maximum potential. As such, their farms are more likely to be less profitable, less competitive, more likely to exit the market, and/or to be subjects of a takeover by better-managed dairy operations. Across smaller dairy operations, it is not uncommon for operators or their spouses to participate in off-farm employment to supplement their income (Prager et al., 2018).

Scale-and-Mix Efficiency in Dairy Farming

Scale-and-mix efficiency refers to productivity gains associated with economies of scale and scope. Economies of scale and substitution are the benefits obtained by a farm as a result of expanding the scale of operations or producing at the optimal scale.[10] Past studies on U.S. dairy farming found evidence of scale economies, largely as a result of dairy operations' expanding capacity (Mosheim and Lovell, 2009). Intensive dairy production practices that use heavy capital have made it possible to expand capacity and optimal scale.

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[9] Somatic cell counts are conducted to gauge milk quality by determining the level of viable aerobic bacteria in raw milk. A high incidence of somatic cell count may be an indicator of unsanitary milking practices, poor udder hygiene, or portend incidences of mastitis in a single cow or the herd.

[10] A key distinction between scale-and-mix efficiency and technical efficiency is scale-and-mix efficiency refers to the optimal scale of operations whereas technical efficiency refers to using inputs at their maximum potential.

Environmental Effects and How They Are Transmitted to Dairy Farming

Long-run climate trends and weather volatility have a direct biophysical effect on agriculture and are transmitted to dairy productivity in four main ways:

- reducing the yield of feed grains;
- lowering the quality and availability of pasture and forage;
- affecting the normal physiological functioning of milk cows as well as their reproductive health; and
- fostering the distribution and resiliency of parasites and pathogens that impact animal health.[11]

Reliable and high-quality water supply is essential in dairy production. It is both consumed directly by cows and it is necessary to grow healthy crops and pasture, as well as to clean and sanitize dairy equipment. Frequent and intense droughts in some dairy production regions exacerbate milk production by raising the risk of heat stress among cows, lowering the yield of feed grains, diminishing the quality and availability of pasture and forage, and ultimately raising the cost of production since diminished water supplies requires operators to obtain water elsewhere at additional cost.

The amount of milk produced from cows is closely linked to their nutrient feed intake, a process that raises the cow's body temperature. A high body temperature, in turn, requires an efficient thermoregulatory mechanism—or a means of preserving a stable core body temperature to maintain temperatures within a specific temperature zone referred to as the thermoneutral zone (Kadzere et al., 2002). The overall physiological well-being of cows is also key to optimal milk production. In warm climates, excess heat must be dissipated. In cooler climates, core temperatures must be preserved to maintain physiological homeostasis. Studies have indicated lactating dairy cows' thermoneutral zone lies between 41°F and 77°F (Roenfeldt, 1998; Kadzere et al., 2002). The thermoneutral zone refers to the optimal upper and lower thresholds of normal heat generated by dairy cows—where normal heat generated by dairy cows due to milk production, feed intake, and nutrient metabolism equals the energy lost to the ambient environment. Temperatures outside these thresholds can negatively affect the cows' normal physiological function. Nonetheless, some of these effects may be ameliorated by implementing adaptive strategies such as housing cows in shade structures, installing cooling systems, altering nutrient mix, and raising heat-tolerant breeds.

The number of days within the calendar year when temperatures fall within the thermoneutral zone are calculated and referred to as optimal thermal days (OTD) and are used to measure the effect of favorable temperatures on milk production. Conversely, the cumulative number of days outside these optimal temperature bands are calculated as harmful degree-days for cows (HDD-cows). These are used to predict the effects of both heat stress and cold stress on milk production.[12]

Similarly, research on crop yields has indicated temperatures affect crop production in a nonlinear fashion (Schlenker and Roberts, 2009). The typical growing season in the United States for corn silage—a common staple that provides carbohydrates and fiber to cows—is from April to September.[13] In addition, the lower-

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[11] Dairy farming is affected by long-run climate trends and weather volatility. Simultaneously, dairy farming is responsible for generating negative environmental externalities such as the generation of methane from the cows, nitrous oxide due to nitrogen loading from using fertilizers and pesticides, and the generation of carbon-dioxide equivalent because of burning of fossil fuels. These externalities are discussed but not estimated in this study.

[12] Temperature humidity index (THI) is a different approach that has been used in past studies to capture the effects of heat stress in milk production (e.g., Key and Sneeringer, 2014; Mukherjee et al., 2013). Some similarities do exist between THI and Heat Degree Day-cows: both approaches predict mild to moderate heat stress above 77°F. However, THI does not capture temperature effects below the lower threshold.

[13] Soybeans, another dairy feed crop, is also typically grown between April to September and has similar growing degree-days as corn. Alfalfa, the other common dairy feed crop, has both spring and fall planting season in some parts of the country.

and upper-bound temperatures required for optimal growth are 50°F and 86°F, respectively. The cumulative days with optimal temperatures are referred to as growing degree-days for crops (GDD). Regions with greater numbers of GDD should typically be more amenable to growing feed crops for cows. Conversely, temperatures above or below the optimal threshold are potentially harmful to crop development and affect both the quality and quantity of feed crops.[14] These are calculated as harmful degree-days for crops (HDD-crops).

Table 1 shows the number of optimal thermal days (OTD) for cows, growing degree-days (GDD) for crops, and harmful degree-days for both crops and cows. The results indicate that Southwestern and Southern States had more optimal thermal days and growing degree-days for crops compared to the upper Midwest and Northeastern States. However, the substantial number of OTD and GDD was partially offset by the considerable number of harmful degree-days for both cows and crops, which are detrimental to dairy farming. This is noteworthy given the rapid growth in dairy operations in some of these regions.

Table 1

Optimal thermal days, growing degree-days, and harmful degree-days, by State, 2000–2016

State	Cows		Crop	
	OTD	HDD	GDD	HDD
Arizona	6953.38	231.1	4715.3	150.75
California	4026.72	157.73	3271.05	95.49
Colorado	2551.4	108.38	2315.35	37.4
Florida	7717.31	257.76	4710.46	138.37
Georgia	5561.14	188.99	4107	86.34
Idaho	2012.65	87.08	2342.7	49.18
Illinois	3626.52	125.71	3127.47	32.16
Indiana	3139.22	110.36	2844.2	18.95
Iowa	2763.31	99.3	2695.44	18.97
Kansas	4290.04	145.41	3351.72	53.79
Kentucky	4330.52	151.8	3492.71	50.05
Maine	1260.12	47.63	1964.44	4.84
Michigan	2328.4	85.21	2386.92	11.37
Minnesota	1981.73	72.94	2443.34	13.6
Missouri	4089.34	139.94	3366.3	45.36
New Mexico	4570.39	173.97	3591.45	107.62
New York	1793.07	66.37	2272.19	7.07
Ohio	3086.51	110.17	2840.71	18.33
Oregon	1072.22	45.64	1971.79	21.66
Pennsylvania	2895.72	102.95	2823.7	20.43
South Dakota	2576.9	94.08	2717.29	20.88
Tennessee	4555.38	161.72	3574.29	52.38
Texas	5879.81	195.18	4317.24	111.9
Utah	1886.15	76.08	2153.84	29

continued on next page ►

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[14] Farms that purchase most of their feed are unlikely to be directly impacted by growing degree-days and harmful degree-days. Nevertheless, such farms will likely experience both a price effect and a quality effect when they purchase feed from outside sources.

◄ continued from previous page

State	Cows		Crop	
	OTD	HDD	GDD	HDD
Virginia	3584.02	129.94	3094.68	32.13
Washington	926.56	38.45	1757.73	19.08
Wisconsin	2043.61	74.45	2379.76	11.71

Notes: OTD=optimal thermal days. GDD=growing degree-days. HDD=harmful degree-days. Optimal thermal days are calculated using maximum and minimum temperature thresholds of 77°F and 41°F, respectively. Growing degree-days are calculated using maximum and minimum temperature thresholds of 86°F and 50°F, respectively. Harmful degree-days for cows (HDD-cows) and harmful degree-days for feed (HDD-feed) aggregate temperatures in excess of 77°F and 86°F, respectively. The estimates for OTD and HDD-cows are for every county, by State, where dairy operations were located between January 1 and December 31 for the years 2000, 2005, 2010, and 2016. The estimates for GDD and HDD-feed are calculated for the growing season April 1 to September 30 for the year prior to when the Agricultural Resource Management Survey on dairy operations were conducted: 1999, 2004, 2009, and 2015. The table includes only States where dairy operations were surveyed under the Agricultural Resource Management Survey. The formulas are provided in appendix B.

Source: USDA, Economic Research Service using data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate group, Oregon State University. Available online.

Trends in Total Factor Productivity Growth

Before estimating total factor productivity (TFP), we needed to track the growth of milk output over time while controlling for inputs used in milk production. These inputs include the number of milk cows, number of labor hours, quantity of purchased feed, quantity of homegrown feed, capital used including machinery and equipment, and intermediate materials, such as expenditures on animal health (veterinarian and medicine), electricity and fuel, chemicals, fertilizers, and bedding. Finally, temperature and rainfall are considered inputs as they directly affect the production process by altering the quality and quantity of feed as well as the normal physiological functioning of the cows. A production function is estimated using these input-output combinations to generate coefficient estimates, which are then used as weights to construct and decompose total factor productivity.

As indicated at the beginning of this section, measuring TFP growth involves computing TFP indexes and then evaluating and analyzing changes in these indexes. TFP, or the ratio of milk output relative to aggregate inputs—that is, $TFP_{it}=Q_{it}/X_{it}$—is calculated for all dairy farms. The variables Q, and X represent quantity of milk produced and aggregate inputs, respectively, for farm i in time period t. Thereafter, the TFP for a single dairy farm—farm k in time period s, is designated as the reference TFP observation, that is, $TFP_{ks}=Q_{ks}/X_{ks}$. Thus, we obtain our TFP index (TFPI) by comparing the TFP_{it} for each dairy farm against the reference dairy farm TFP_{ks}. That is, $TFPI_{ksit}=[Q_{it}/X_{it}]/[Q_{ks}/X_{ks}]$. Finally, TFP growth is measured by analyzing changes in total factor productivity index (TFPI) across all farms between 2000 and 2016.[15]

Estimates of TFP growth by herd-size class are shown in table 2. These results indicate the fastest TFP growth rate—2.993 percent per year—was generated by dairy operations with more than 1,000 milk cows.[16] Meanwhile, TFP growth for the smallest herd-size class with 1–100 milk cows increased at an annual rate of 0.639 percent. TFP growth across all herd-size classes was primarily driven by technological progress (TPI) and environmental effects that positively impacted the availability of feed (EI-feed). On the other hand, TFP growth declined, driven by reductions in scale-and-mix efficiency (SMEI), technical efficiency (TEI), and unfavorable environmental factors that impact the general well-being of cows (EI-cows).

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[15] The total factor productivity index (TFPI) numbers for the reference farm in the year 2000 and the comparison farm in the year 2016 are 1.1206 and 2.2328, respectively. Therefore the percent change in TFPI is computed as $(2.2328/1.1206)^{1/(2016-2000)}-1=0.04403=4.403$ percent. Note that this is the average percent change TFPI for dairy operations in Idaho shown in table 3.

[16] Today, most cows are in the 1,000+ herd-size class. When the dairy component of ARMS was first conducted in 2000, there were fewer dairy operations in the 1,000+ herd-size class. The five class sizes are retained to maintain consistent comparisons across the years.

Table 2

Average total factor productivity growth for herd-size classes in 2016 relative to the reference farm in 2000

Herd-size class	TFPI (percent change)	TPI (percent change)	SMEI (percent change)	TEI (percent change)	EI-feed (percent change)	EI-cows (percent change)
1–100	0.639	3.172	-1.782	-1.617	5.123	-1.098
101–250	1.965	3.362	-1.013	-1.246	3.271	-0.616
251–500	2.255	3.355	-0.838	-1.166	2.950	-0.563
501–999	2.711	3.432	-0.562	-1.170	2.019	-0.440
1,000+	2.993	3.490	-0.373	-1.157	1.331	-0.375

Notes: TFPI = total factor productivity index. TPI = technological progress index. SMEI = scale-and-mix efficiency index. TEI = technological efficiency index. EI = environmental index. Multiplicative index is used to decompose total factor productivity index (TFPI). It is the product of technological progress index (TPI), scale-and-mix efficiency index (SMEI), environmental index (EI), and technical efficiency index (TEI), as well as an unobserved log-index (not included in the table), which measures statistical noise. Additional notes on methods are provided in the appendix C following equation 11.

Source: USDA, Economic Research Service using USDA, Economic Research Service, and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data.

A State-by-State analysis of TFP growth is provided in table 3. These numbers were calculated as described above. That is, the growth rate in TFP was calculated by compounding the TFPI for the reference farm in 2000 at a constant rate to obtain TFPI for the comparison State in 2016. The State with the fastest-growing TFP was Idaho at 4.403 percent; the slowest-growing State was Tennessee at 0.899 percent per year. The average TFP growth rate from 2000 to 2016 across all States was 2.517 percent. This was primarily driven by changes in technological progress (TPI), which grew at an annual rate of 3.469 percent. The rate of growth of TFP was held back by substantial declines in scale-and-mix efficiency (SMEI), technical efficiency (TEI), and negative environmental impacts on cow comfort (EI-cows). Figures 10 and 11 illustrate productivity by herd size and across select States, respectively. Appendix A provides additional details on all data sources used in this analysis, the econometric procedures followed, and the TFP decomposition methods.

Table 3

Average total factor productivity growth by State in 2016 relative to the reference farm in 2000

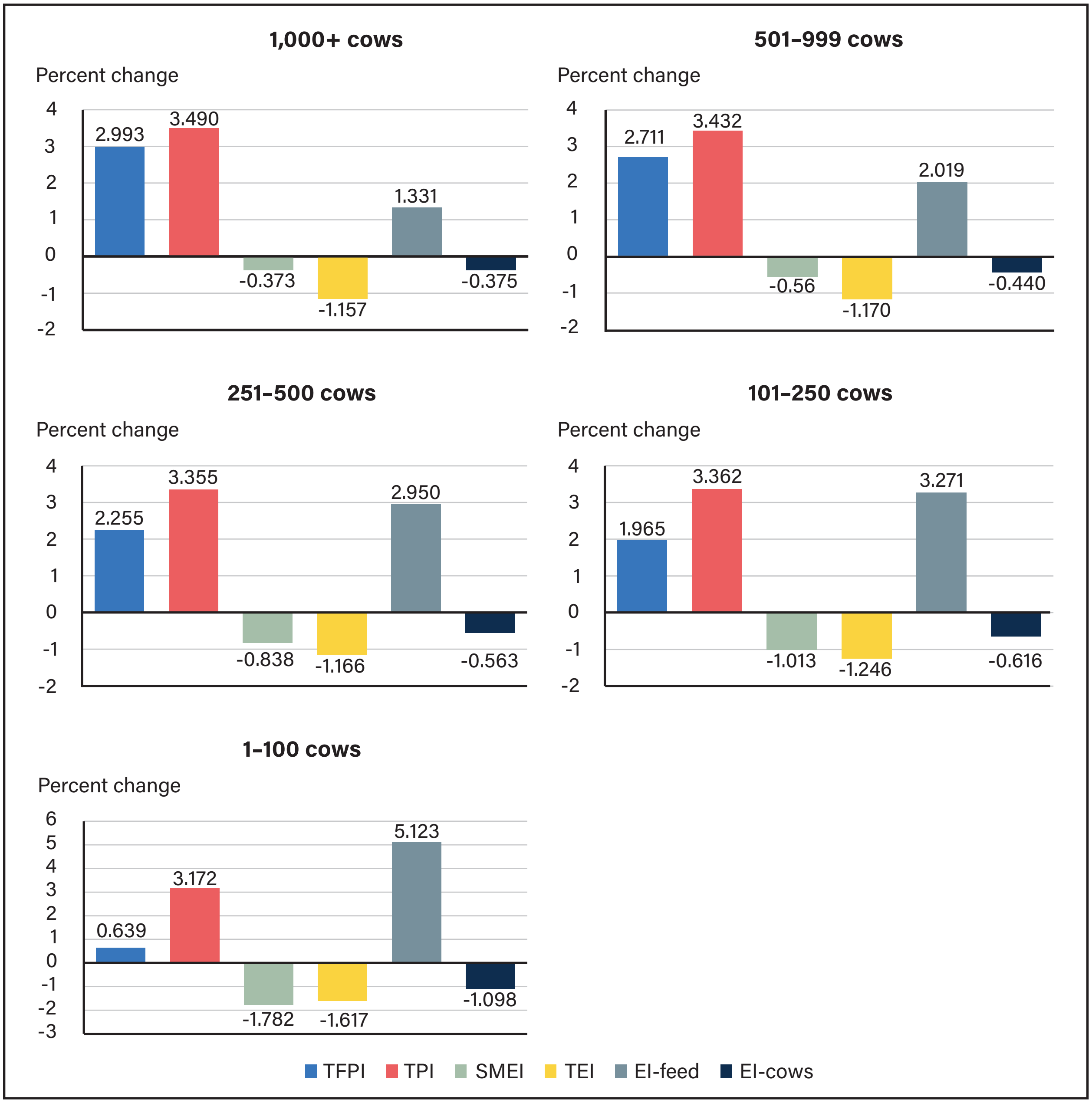
State	TFPI (percent change)	TPI (percent change)	SMEI (percent change)	TEI (percent change)	EI-feed (percent change)	EI-cows (percent change)
Idaho	4.403	3.595	-0.010	-0.796	0.536	-0.210
New Mexico	4.350	3.776	0.390	-1.284	0.767	0.056
Arizona	3.973	3.776	0.263	-0.649	-0.794	-0.190
California	3.526	3.589	0.126	-1.441	-0.963	-0.189
Colorado	3.074	3.396	-0.573	-0.691	1.523	-0.793
Iowa	2.951	3.458	-0.752	-1.102	3.149	-0.413
Wisconsin	2.930	3.345	-0.800	-0.966	3.713	-0.569
Minnesota	2.924	3.359	-0.728	-0.960	3.023	-0.575
South Dakota	2.833	3.491	-0.625	-0.764	1.903	-0.422
Washington	2.714	3.459	-0.244	-1.685	0.917	-0.322
Utah	2.623	3.301	-0.480	-0.865	1.021	-0.691
New York	2.615	3.447	-0.748	-0.935	2.885	-0.558
Ohio	2.565	3.437	-0.830	-0.989	3.104	-0.353
Michigan	2.552	3.376	-0.726	-1.286	2.858	-0.505
Pennsylvania	2.388	3.492	-0.998	-1.223	3.538	-0.401
Virginia	2.340	3.479	-0.756	-1.134	2.866	-0.283
Texas	2.269	3.412	-0.203	-1.303	0.647	0.075
Maine	2.265	3.371	-0.906	-0.990	3.261	-0.913
Oregon	2.159	3.445	-0.501	-1.386	0.697	-0.837
Indiana	2.068	3.436	-1.016	-1.240	3.816	-0.430
Vermont	2.042	3.251	-0.742	-0.915	2.944	-0.648
Florida	2.027	3.719	0.017	-1.240	0.037	-0.140
Kansas	1.906	3.572	-1.144	-1.484	4.193	-0.214
Illinois	1.788	3.352	-0.937	-1.321	3.542	-0.199
Kentucky	1.748	3.341	-0.956	-1.272	4.048	-0.239
Georgia	1.275	3.484	-0.737	-1.536	1.832	-0.074
Missouri	1.261	3.418	-1.184	-1.209	4.105	-0.230
Tennessee	0.899	3.553	-1.031	-1.297	2.439	-0.265
Arithmetic Average	2.517	3.469	-0.601	-1.142	2.200	-0.376

Notes: TFPI = total factor productivity index. TPI = technological progress index. SMEI = scale-and-mix efficiency index. TEI = technological efficiency index. EI = environmental index. The components described include percentage changes in total factor productivity index (TFPI), technological progress index (TPI), scale-and-mix efficiency index (SMEI), technical efficiency index (TEI), environmental index-feed (EI-feed), and environmental index-cows (EI-cows). $TFPI_{ksit}$ is calculated as aggregate milk output relative to aggregate inputs for dairy farm *i* in period *t* relative to that of dairy farm *k* in time period *s*, that is, $[Q_{it}/X_{it}]/[Q_{ks}/X_{ks}]$. Thereafter, percentage change in TFPI is measured by analyzing changes in TFPI across all farms between 2000 and 2016 using dairy operations in Arizona in 2000 as the base State and year, respectively. The table includes only States where dairy operations were surveyed under the Agricultural Resource Management Survey. Dairy operations in South Dakota and Utah were surveyed for the first time in 2016. Dairy operations in Colorado and Kansas were surveyed in 2010 and 2016, and dairy operations in Maine and Oregon were surveyed across the years 2005, 2010, and 2016. Finally, dairy operations across the other States listed were surveyed across the years 2000, 2005, 2010, and 2016.

Source: USDA, Economic Research Service using USDA, Economic Research Service, and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data

Figure 10

Average total factor productivity growth for herd-size classes in 2016 relative to the reference farm in 2000

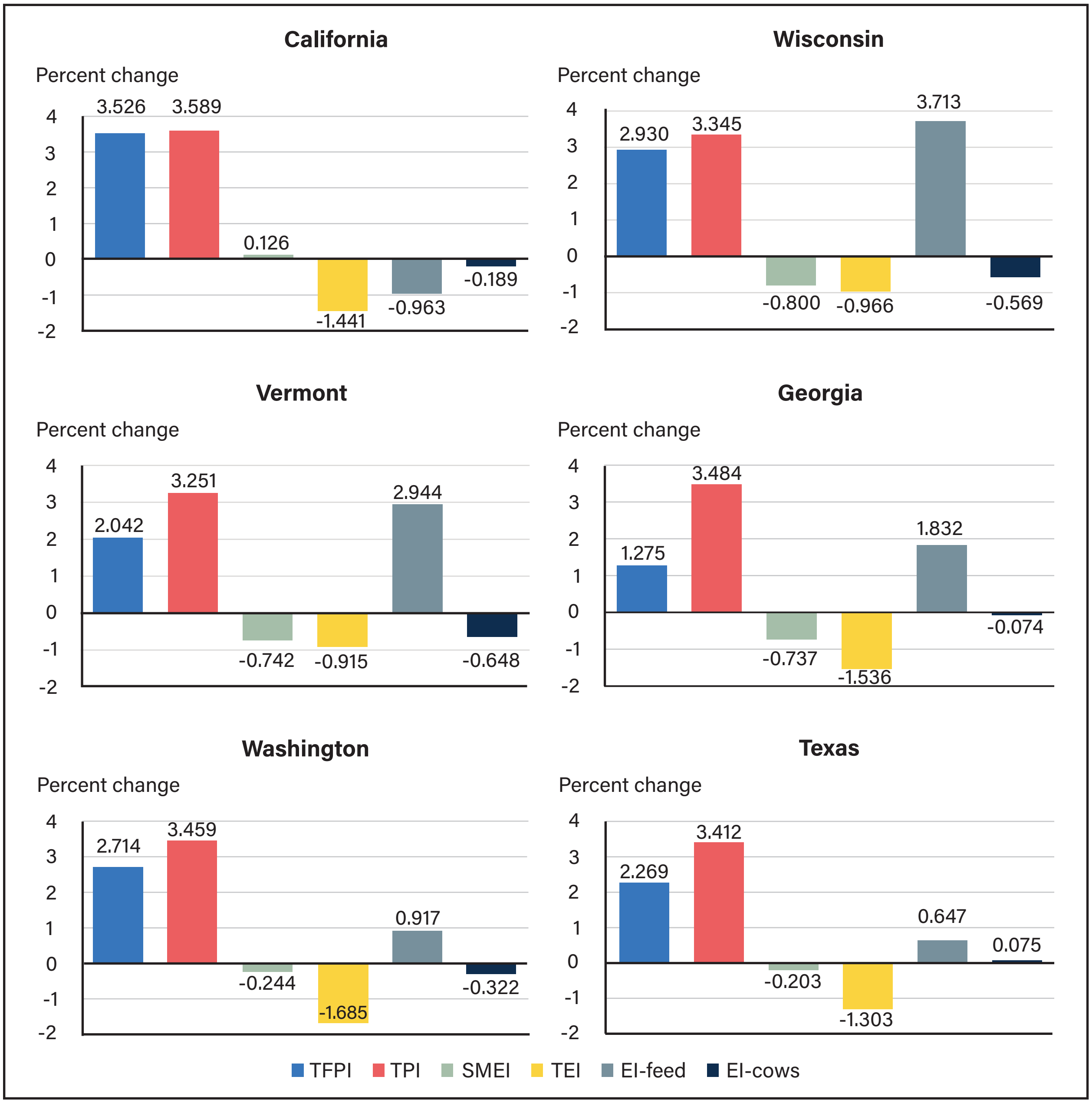


Notes: TFPI = total factor productivity index. TPI = technological progress index. SMEI = scale-and-mix efficiency index. TEI = technological efficiency index. EI = environmental index. Figure 10 illustrates percent change in TFPI and its components for five herd-size classes: 1–100, 101–250, 251–500, 501–999, and 1,000+.

Source: USDA, Economic Research Service using USDA, Economic Research Service, and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data.

Figure 11

Average total factor productivity growth for select States in 2016 relative to the reference farm in 2000



Notes: TFPI = total factor productivity index. TPI = technological progress index. SMEI = scale-and-mix efficiency index. TEI = technological efficiency index. EI = environmental index. Figure 11 illustrates the percent change for TFPI and its components across six geographically diverse States: California, Wisconsin, Vermont, Georgia, Washington, and Texas.

Source: USDA, Economic Research Service using USDA, Economic Research Service, and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data.

Organic Dairy Farming

In 2019, milk from organic dairy farms comprised 2.35 percent of total milk sales in the United States,[17] according to the USDA, National Agricultural Statistics Service (NASS). Here, organic refers to how the animals are raised. Organic dairy farms are subject to stringent regulations to obtain certification and maintain their organic status. For example, pastures on organic farms, including bedding used for animal housing, must be certified organic. Antibiotics, Genetically Modified Organism (GMO)-derived products, animal by-products, and synthetic preservatives are not permitted in any feed products given to cattle. Similarly, administering any animal drugs such as antibiotics in the absence of illness is prohibited, and even then, such instances must be reported. Further, the use of growth hormones like recombinant bovine somatotropin (rBST) to promote growth and increase milk production is prohibited.[18]

Moreover, the transition from conventional to organic production can be costly for some operations. For example, USDA guidelines require at least a 12-month transition period during which dairy cows should not be provided with feed grain grown with synthetic chemicals. This regulation is in addition to even more stringent standards including substantial pasture requirements per cow, year-round access to the outdoors for the organic milk cows, soil fertility management with regular testing, and at least a 3-year transition period for fields since the last application of prohibited synthetic pesticides and fertilizers. Furthermore, animal housing regulations prohibit the housing of young organic stock with non-certified cows.

However, the environmental benefits of organic dairy are numerous. Some of the environmental benefits include a reliance on pastures that aid in carbon storage,[19] lower methane emissions because less manure is stored in lagoons and slurry pits, and lower nitrous oxide emission because of the avoidance of synthetic fertilizers and pesticides (O'Brien et al., 2012; McCarthy et al., 2016). In addition, organic dairy producers are required to complete a pasture plan that includes erosion control and natural-wetland protections, so organic dairy farms are likely not major contributors to water body eutrophication. However, because organic dairy is a niche market, organic milk must be pasteurized, and in some States, transported long distances to markets, requiring additional energy consumption that could potentially offset the environmental benefits. The TFP method applied here to measure productivity growth does not capture some of the benefits that organic dairy farming generates—or what is referred to in economics as the social marginal benefits.

Given current production levels, organic dairy products are generally priced higher, which consumers are willing to pay. For example, in 2016, organic dairy producers—on average—earned $38.46 per hundredweight (cwt), whereas conventional dairy producers received an average of $16.30 per cwt.[20] Similarly, the gross milk returns for organic dairy operations were—on average—higher compared with gross milk returns for conventional dairy operations. Net returns, which comprise the difference between gross returns and total costs, were negative for organic dairy producers in operations with fewer than 100 milk cows—whereas for conventional dairy operations, net returns were negative for all herd-size classes except the largest with more than 2,000 milk cows (MacDonald et al., 2020). These market dynamics have generally enabled medium-sized organic dairy producers to remain viable, whereas conventional dairy operations would need to scale-up substantially in order to remain profitable.

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[17] For more information, see USDA, National Agricultural Statistics Service (NASS) *Quickstats*, available online.

[18] For more information, see USDA's Guidelines for Organic Certification of Dairy Livestock, available online.

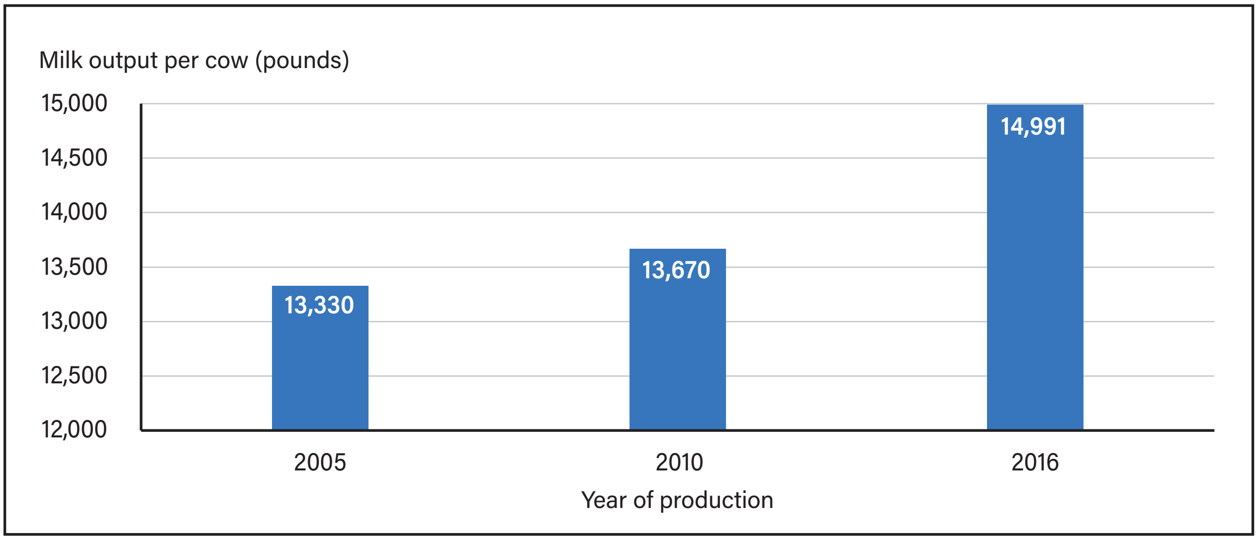
[19] Not all organic dairy operations are pasture-based. The organic standard states 30 percent of dry matter intake must come from pasture during the grazing season.

[20] For more information, view USDA, National Agricultural Statistics Service (NASS) *Quickstats*, available online.

Organic dairy operations have been surveyed by USDA, Economic Research Service (ERS) and USDA, National Agricultural Statistics Service (NASS) under the Agricultural Resource Marketing Survey (ARMS) beginning in 2005. Cost and returns estimates from ARMS indicate milk yields from organic dairy operations were much lower compared with the conventional dairy operations. In 2016, milk yields from organic operations averaged 14,991 pounds per cow compared with 24,185 pounds per cow from their conventional counterparts. (See figure 4 for conventional and figure 12 for organic dairy farms.)

Figure 12

Milk output per cow for organic dairy farms, 2005–2016



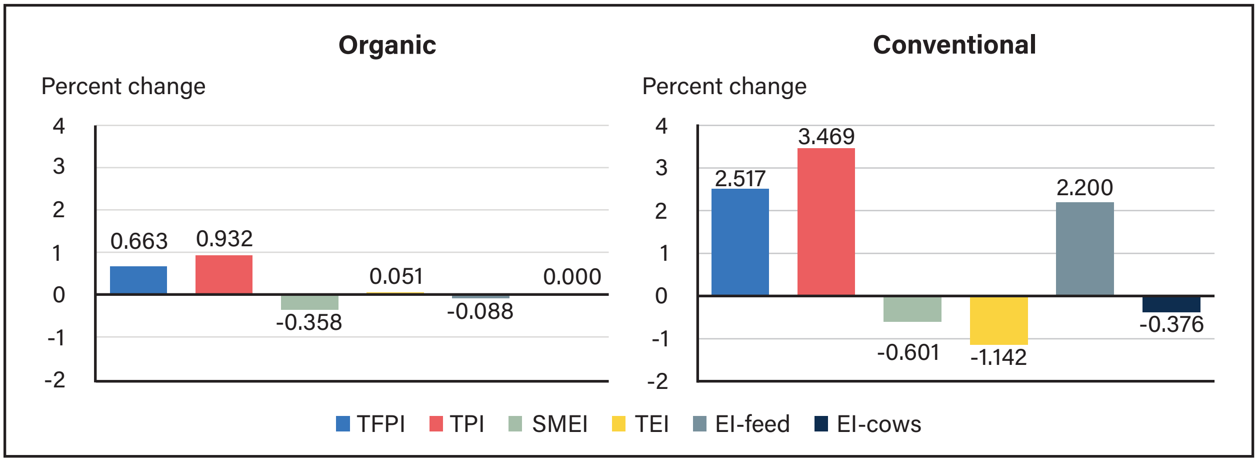
Note: Organic dairy farms were surveyed for the first time in 2005, then subsequently in 2010 and 2016.

Source: USDA, Economic Research Service using USDA, Economic Research Service, and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data.

Organic dairy operations face significant production challenges. They use fewer labor-saving devices, hence incurring higher labor-related costs. Organic dairy operations mostly rely on pasture-based feeding, and thus they are potentially more vulnerable to weather shocks and anomalies. In addition, they may face difficulties sourcing organic inputs such as grains and forages, feed supplements, and replacement heifers (McBride and Greene, 2009). Evidence of these challenges are discernible in the TFP growth number generated. TFP grew at a modest annual rate of 0.66 percent for organic dairy farms compared with 2.51 percent among conventional dairy operations. Scale-and-mix efficiency declined substantially, which demonstrates organic farms did not operate at the optimal scale. Compared with conventional dairy operations, organic dairy operations faced negative environmental effects because of feed availability, underscoring their vulnerability in finding organic feed products (figure 13).

Figure 13

Average total factor productivity growth for organic dairy farms (2005-2016) and conventional dairy farms (2000–2016)



Notes: TFPI = total factor productivity index. TPI = technological progress index. SMEI = scale-and-mix efficiency index. TEI = technological efficiency index. EI = environmental index. Figure 13 illustrates the percent change for TFPI and the percent change for its components: TPI, SMEI, TEI, and EI-feed and EI-cows for organic and conventional dairy farms. The base year for organic dairy farms is 2005, whereas the base year for conventional farms is 2000.

Source: USDA, Economic Research Service using USDA, Economic Research Service, and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data.

Conclusions

The U.S. dairy sector has been characterized by consolidation and rapid structural adjustments marked by a shift in production away from small farms towards large dairy operations. From 2000 to 2016, the average annual growth rate across conventional dairy farms was 2.51 percent. Total factor productivity (TFP) growth in the U.S. agricultural sector was 0.97 percent over the same period. Technological progress—characterized by the discovery of new systems, processes, and methods in dairy production—was the primary driver behind the sustained productivity growth in the dairy sector.

TFP growth was widespread but with considerable variations across regions and by herd-size class. The fastest-growing States were in the West and Southwest, including Idaho, New Mexico, Arizona, and California. However, the slowest-growing States were generally located in the South—Tennessee, Missouri, Georgia, and Kentucky. Furthermore, large dairy operations grew faster than their smaller counterparts, providing evidence that an increase in scale of operations is beneficial for productivity. Finally, organic operations experienced much slower TFP growth compared with their conventional counterparts. On average, environmental effects affecting feed availability contributed positively TFP growth. On the other hand, environmental effects affecting cow wellbeing were significantly negative and varied by State and by herd-size class. This may signal some dairy operations are having trouble mitigating the effects of weather anomalies.

Results from measuring and evaluating sources and drivers of productivity and efficiency in dairy farming can be used to understand and address shortfalls in the sector if increasing productivity is the intended goal. For example, if productivity shortfalls are due to declining technical efficiency, then actions may be needed to provide education and training to farmers on how to successfully combine various inputs in order to produce at full potential. Similarly, if productivity shortfalls are due to declining scale-and-mix efficiency, producers may need to be encouraged to increase their scale of operations. And if technological progress is the main driver as we find in this study, then a mix of investments in research and development, as well as encouraging diffusion and adoption of new technology by farmers, may be needed. Finally, environmental effects and how they are transmitted to dairy farming are identified and evaluated. These measures can be used to provide training and information to farmers on regions where improvements can be made in cow wellbeing while ensuring a steady supply of food sources for the livestock.

References

Adhikari, M., K.P. Paudel, N.R. Martin Jr, and W.M. Gauthier. 2005. "Economics of Dairy Waste Use as Fertilizer in Central Texas," *Waste Management* 25(10):1067–1074.

American Society of Agricultural and Biological Engineers. 2005. "Manure Production and Characteristics - ASAE D384.2," American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Cessna, J., L. Kuberka, C. Davis, and R. Hoskin. 2016. *Growth of U.S. Dairy Exports*, LDPM-270-01, U.S. Department of Agriculture, Economic Research Service.

Cessna, J., and A. Teran. 2021. "Livestock, Dairy, and Poultry Outlook," *World Agricultural Supply and Demand Estimates*, LDP-M-322, U.S. Department of Agriculture, Economic Research Service.

Cole, J.B., S.A.E. Eaglen, C. Maltecca, H.A. Mulder, and J.E. Pryce. 2020. "The Future of Phenomics in Dairy Cattle Breeding," *Animal Frontiers* 10(2):37–44.

Davis, C., and J. Cessna. 2020. *Prospects for Growth in U.S. Dairy Exports to Southeast Asia*, ERR-278, U.S. Department of Agriculture, Economic Research Service.

Erickson, P.S., and K.F. Kalscheur. 2020. "Nutrition and Feeding of Dairy Cattle," *Animal Agriculture*:157–180.

Foldager, L., P. Trenel, L. Munksgaard, and P.T. Thomsen. 2020. "Technical Note: Random Forests Prediction of Daily Eating Time of Dairy Cows from 3-Dimensional Accelerometer and Radiofrequency Identification," *Journal of Dairy Science* 103(7):6271–6275.

Garćia-Ruiz, A., J.B. Cole, P.M. VanRaden, G.R. Wiggans, F.J. Ruiz-López, and C.P. Van Tassell. 2016. "Changes in Genetic Selection Differentials and Generation intervals in US Holstein Dairy Cattle as a Result of Genomic Selection," *Proceedings of the National Academy of Sciences* 113(33):E3995–E4004.

Guinan, F.L., H.D. Norman, and J.W. Dürr. 2019. "Changes Occurring in the Breed Composition of U.S. Dairy Herds," *Interbull Bulletin* 55:11–16.

Halachmi, I., M. Guarino, J. Bewley, and M. Pastell. 2019. "Smart Animal Agriculture: Application of Real-Time Sensors to Improve Animal Well-Being and Production," *Annual Review of Animal Biosciences* 15(7):403–425.

Hayami, Y., and V.W. Ruttan. 1971. *Agricultural Development: An International Perspective*. Baltimore, MD: Johns Hopkins University Press.

Hoffman, P.C., N.M. Brehm, S.G. Price, and A. Prill-Adams. 1996. "Effect of Accelerated Postpubertal Growth and Early Calving on Lactation Performance of Primiparous Holstein Heifers," *Journal of Dairy Science* 79(11):2024–2031.

Holden, S.A., and S.T. Butler. 2018. "Review: Applications and Benefits of Sexed Semen in Dairy and Beef Herds," *Animal* 12(s1):s97–s103.

Huang, C., T.H. Huang, and N.H. Liu. 2014. "A New Approach to Estimating the Metafrontier Production Function Based on a Stochastic Frontier Framework," *Journal of Productivity Analysis* 42(3):241–254.

Kadzere, C.T., M.R. Murphy, N. Silanikove, and E. Maltz. 2002. "Heat Stress in Lactating Dairy Cows: A Review," *Livestock Production Science* 77:59–91.

Key, N., and S. Sneeringer. 2014. "Potential Effects of Climate Change on the Productivity of U.S. Dairies," *American Journal of Agricultural Economics* 96(4):1136–1156.

Key, N., S. Sneeringer, and D. Marquardt. 2014. *Climate Change, Heat Stress, and U.S. Dairy Production*, ERR-175, U.S. Department of Agriculture, Economic Research Service.

Krápalková, L., V.E. Cabrera, J. Kvapilik, J. Burdych, and P. Crump. 2014. "Associations Between Age at First Calving, Rearing Average Daily Weight Gain, Herd Milk Yield and Dairy Herd Production, Reproduction and Profitability," *Journal of Dairy Science* 97(10):6573–6582.

Kumbhakar, S.C., and C.A.K. Lovell. 2000. *Stochastic Frontier Analysis*. Cambridge, UK: Cambridge University Press.

MacDonald, J.M., J. Cessna, and R. Mosheim. 2016. *Changing Structure, Financial Risks, and Government Policy for the U.S. Dairy industry*, ERR-205, U.S. Department of Agriculture, Economic Research Service.

MacDonald, J.M., R.A. Hoppe, and D. Newton. 2018. *Three Decades of Consolidation in U.S. Agriculture*, EIB-189, U.S. Department of Agriculture, Economic Research Service.

MacDonald, J.M., J. Law, and R. Mosheim. 2020. *Consolidation in U.S. Dairy Farming*, ERR-274, U.S. Department of Agriculture, Economic Research Service.

MacDonald, J.M., E.J. O'Donoghue, W.D. McBride, R.F. Nehring, C.L. Sandretto, and R. Mosheim. 2007. *Profits, Costs, and the Changing Structure of Dairy Farming*, ERR-47, U.S. Department of Agriculture, Economic Research Service.

McBride, W.D., and C. Greene. 2009. *Characteristics, Costs, and Issues for Organic Dairy Farming*, ERR-82, U.S. Department of Agriculture, Economic Research Service.

McCarthy, B., L. Delaby, K.M. Pierce, J. McCarthy, C. Fleming, A. Brennan, and B. Horan. 2016. "The Multi-Year Cumulative Effects of Alternative Stocking Rate and Grazing Management Practices on Pasture Productivity and Utilization Efficiency," *Journal of Dairy Science* 99(5):3784–3797.

Miller, G.A., M. Mitchell, Z.E. Barker, K. Giebel, E.A. Codling, J.R. Amory, C. Michie, C. Davison, C. Tachtatzis, I. Andonovic, and C.-A. Duthie. 2020. "Using Animal-Mounted Sensor Technology and Machine Learning to Predict Time-to-Calving in Beef and Dairy Cows," *Animal* 14(6):1304–1312.

Mosheim, R., and C.A.K. Lovell. 2009. "Scale Economies and Inefficiency of U.S. Dairy Farms," *American Journal of Agricultural Economics* 91(3):777–794.

Mukherjee, D., B.E. Bravo-Ureta, and A. De Vries. 2013. "Dairy Production and Climatic Conditions: Econometric Evidence from South-eastern United States," *Australian Journal of Agricultural and Resource Economics* 57(1):123–140.

O'Brien, D., L. Shalloo, J. Patton, F. Buckley, C. Grainger, and M. Wallace. 2012. "A Life Cycle Assessment of Seasonal Grass-Based and Confinement Dairy Farms," *Agricultural Systems* 107:33–46.

O'Donnell, C.J. 2018. *Productivity and Efficiency Analysis: An Economic Approach to Measuring and Explaining Managerial Performance*. New York, NY: Springer Publishing.

Olley, S.G., and A. Pakes. 1996. “The Dynamics of Productivity in the Telecommunications Equipment Industry,” *Econometrica* 64:1263–1297.

Dinsmore, R. P. 2015. “Animal and Herd Productivity in Dairy Cattle,” *Merck Manual: Veterinary Manual*.

Paudel, K.P., K. Bhattarai, W.M. Gauthier, and L.M. Hall. 2009. “Geographic Information Systems (GIS) Based Model of Dairy Manure Transportation and Application with Environmental Quality Consideration,” *Waste Management* 29(5):1634–1643.

Prager, D.L., S. Tulman, and R. Durst. 2018. *Economic Returns to Farming for U.S. Farm Households*, ERR-254, U.S. Department of Agriculture, Economic Research Service.

Roenfeldt, S. 1998. “You Can’t Afford to Ignore Heat Stress,” *Dairy Herd Management* 35(5):6–12.

Schlenker, W., and M.J. Roberts. 2009. “Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields Under Climate Change,” *Proceedings of the National Academy of Sciences* 106(37):15594–15598.

United Nations, Food and Agriculture Organization. 2020. “Dairy Market Review: Overview of Global Dairy Market Developments in 2019,” Food and Agriculture Organization, Rome, Italy.

U.S. Department of Agriculture, Animal and Plant Health Inspection Service. 2018. *Health and Management Practices on U.S. Dairy Operations, 2014*, Report 3, U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Riverdale, MD.

U.S. Department of Agriculture, Animal and Plant Health Inspection Service. 2016. *Milk Quality, Milking Procedures, and Mastitis on U.S. Dairies, 2014*, Report 2, U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Riverdale, MD.

U.S. Department of Agriculture, Economic Research Service. 2020. *Cash Receipts by Commodity: Dairy Products*, *Milk, Farm Income and Wealth Statistics*, U.S. Department of Agriculture, Economic Research Service, Kansas City, MO.

U.S. Department of Agriculture, National Agricultural Statistics Service. 2004. *2002 Census of Agriculture*, U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

U.S. Department of Agriculture, National Agricultural Statistics Service. 2019. *2017 Census of Agriculture*, U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

Wolfenson, D., and Z. Roth. 2018. “Impact of Heat Stress on Cow Reproduction and Fertility,” *Animal Frontiers* 9(1):32–38.

Zellner, A., J. Kmenta, and J. Dreze. 1966. “Specification and Estimation of Cobb-Douglas Production Function Models,” *Econometrica* 34(4):784–795.

Appendix A: Data Sources Used in this Report

The analysis on milk output per cow relies on data from the milk production report prepared by USDA, National Agricultural Statistics Service (NASS). The data include average milk production per cow and inventories of milk cows by State from 2000 to 2020.

Table A1

Milk cow inventory and milk output per cow, 2000–2020

State	Average milk production (lbs)	Average milk production per head (lbs)	Average number of milk cows
Alabama	167,238,095.24	14,053.57	11,857
Alaska	8,542,105.26	12,205.74	674
Arizona	4,218,476,190.48	23,395.24	179,762
Arkansas	200,238,095.24	12,830.90	15,762
California	39,090,904,761.90	22,471.52	1,737,905
Colorado	3,147,476,190.48	23,690.10	130,905
Connecticut	398,809,523.81	19,988.90	20,048
Delaware	107,214,285.71	17,683.86	6,181
Florida	2,309,904,761.90	18,165.48	128,190
Georgia	1,550,333,333.33	19,019.38	81,524
Hawaii	51,473,684.21	14,063.26	3,668
Idaho	12,161,857,142.86	22,983.05	524,429
Illinois	1,910,571,428.57	19,141.90	100,333
Indiana	3,497,000,000.00	20,619.29	168,571
Iowa	4,455,619,047.62	21,235.52	209,524
Kansas	2,697,952,380.95	21,008.95	126,619
Kentucky	1,222,238,095.24	15,177.43	84,048
Louisiana	319,809,523.81	12,729.14	25,762
Maine	612,333,333.33	18,996.24	32,429
Maryland	1,049,333,333.33	18,258.76	58,714
Massachusetts	258,761,904.76	17,713.33	14,714
Michigan	8,514,428,571.43	23,279.10	361,095
Minnesota	9,067,047,619.05	19,436.67	467,476
Mississippi	273,333,333.33	14,557.38	18,905
Missouri	1,555,476,190.48	14,769.00	105,381
Montana	311,095,238.10	20,191.52	15,571
Nebraska	1,222,047,619.05	20,304.00	60,619
Nevada	618,333,333.33	21,863.76	28,143
New Hampshire	286,666,666.67	19,751.57	14,619
New Jersey	158,619,047.62	17,603.81	9,190
New Mexico	7,471,190,476.19	23,321.76	319,619
New York	13,127,857,142.86	20,776.76	633,857
North Carolina	972,619,047.62	19,556.00	50,333
North Dakota	420,238,095.24	17,750.38	25,286
Ohio	5,101,571,428.57	19,182.24	266,143
Oklahoma	988,714,285.71	17,036.86	59,143

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State	Average milk production (lbs)	Average milk production per head (lbs)	Average number of milk cows
Oregon	2,337,857,142.86	19,766.29	117,952
Pennsylvania	10,607,476,190.48	19,500.38	545,381
Rhode Island	18,057,142.86	17,441.67	1,048
South Carolina	286,047,619.05	17,248.10	16,619
South Dakota	1,957,095,238.10	19,767.86	97,524
Tennessee	916,904,761.90	16,097.10	57,905
Texas	8,982,142,857.14	20,763.62	423,143
Utah	1,939,619,047.62	21,025.29	92,095
Vermont	2,623,761,904.76	19,144.24	137,667
Virginia	1,736,857,142.86	17,951.95	97,714
Washington	6,044,000,000.00	23,478.19	257,095
West Virginia	169,095,238.10	15,259.86	11,095
Wisconsin	26,094,857,142.86	20,589.14	1,267,381
Wyoming	114,309,523.81	19,384.19	5,776

Notes: lbs=pounds. California, Wisconsin, and Idaho had the largest inventories of milk cows and the highest milk producers.

Source: USDA, Economic Research Service using USDA, National Agricultural Statistics Service, Milk Production report data.

This study also reported milk output by breed and by herd-size class using data from the Dairy Herd Improvement Association (DHIA), which is part of the Council on Dairy Cattle Breeding (CDCB). DHIA took over data reporting done by the USDA, Agricultural Research Service, Animal Genomics and Improvement Laboratory. The reporting is based on regional DHIAs.

Table A2

Milk output per cow (in pounds) by breed, 2000–2019

Year\Breed	Ayrshire	Brown Swiss	Guernsey	Holstein	Jersey	Milking Shorthorn	Mixed Breeds
2000	15,529	17,478	14,626	21,536	15,188	16,929	17,362
2001	15,526	17,477	14,890	21,560	15,350	17,011	17,369
2002	15,878	17,847	14,931	21,919	15,652	14,218	17,707
2003	15,560	17,801	14,918	21,943	15,745	14,134	17,643
2004	15,375	17,473	15,143	21,946	15,739	14,093	17,805
2005	15,782	17,977	15,284	22,610	16,200	14,345	18,221
2006	15,562	18,218	15,586	22,833	16,250	14,090	18,017
2007	15,765	18,149	15,610	22,946	16,266	13,932	18,380
2008	15,502	18,322	15,524	23,022	16,489	13,023	18,524
2009	15,353	18,476	15,361	23,151	16,438	12,992	18,980
2010	15,602	18,742	15,579	23,470	16,735	13,623	19,601
2011	15,450	18,505	15,259	23,692	16,938	12,708	19,669
2012	15,368	18,786	15,618	24,092	17,152	14,158	20,349
2013	15,256	19,013	15,610	24,507	17,644	14,262	20,631
2014	15,003	18,575	15,704	24,953	18,057	14,124	21,312
2015	15,304	19,125	15,815	25,293	18,158	14,402	21,782

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Year\Breed	Ayrshire	Brown Swiss	Guernsey	Holstein	Jersey	Milking Shorthorn	Mixed Breeds
2016	15,199	19,378	15,703	25,558	18,314	14,583	21,951
2017	15,310	19,295	15,620	25,676	18,455	14,188	22,234
2018	16,112	19,121	15,122	25,669	18,161	14,152	21,809
2019	15,748	19,310	14,794	25,946	18,098	13,587	21,840

Source: USDA, Economic Research Service using Council on Dairy Cattle Breeding, Dairy Herd Improvement Association data.

Table A3

Milk output per cow (in pounds) by herd-size class, 2000–2019

Year\Herd-size class	1–199	200–299	300–499	500–749	750–999	1,000–1,999	2,000+
2000	19,187	20,456	21,375	22,026	22,240	22,507	22,464
2001	19,131	20,428	21,226	22,058	22,090	22,434	22,471
2002	19,365	20,711	21,485	22,341	22,357	22,645	22,941
2003	19,298	20,766	21,281	22,447	22,529	22,682	22,953
2004	19,278	20,645	21,232	22,315	22,480	22,623	22,952
2005	19,697	21,445	21,856	22,922	23,211	23,309	23,536
2006	19,847	21,612	22,170	23,053	23,324	23,382	23,540
2007	19,749	21,486	22,337	23,033	23,520	23,677	23,520
2008	19,634	21,538	22,411	23,077	23,490	23,717	23,439
2009	19,613	21,659	22,384	23,366	23,689	23,757	23,325
2010	19,735	21,936	22,715	23,577	23,912	24,002	23,523
2011	19,567	21,896	22,763	23,511	24,368	24,212	24,001
2012	19,838	22,322	23,187	23,926	24,697	24,691	24,264
2013	19,979	22,518	23,571	24,464	24,978	24,991	24,573
2014	20,147	22,858	24,028	24,886	25,379	25,427	25,001
2015	20,490	23,185	24,404	25,070	25,636	25,754	25,067
2016	20,521	23,264	24,506	25,430	25,675	25,828	25,537
2017	20,604	23,482	24,589	25,600	25,558	25,641	25,611
2018	20,409	23,369	24,439	25,134	25,578	25,551	25,447
2019	20,161	23,219	24,291	25,330	25,830	25,711	25,674

Source: USDA, Economic Research Service using Council on Dairy Cattle Breeding, Dairy Herd Improvement Association data.

Finally, the analysis on total factor productivity (TFP) was conducted using data from the Agricultural Resource Management Survey (ARMS). The information comprises farm-level cost and returns and production practices from Phase III surveys conducted in 2000, 2005, 2010, and 2016. The variables used include milk output in hundredweights (cwt), milk-cow inventory, homegrown and purchased feed, family labor and hired labor hours, depreciation expenses and interest rates paid, and expenses on veterinary, electricity and fuel, fertilizers, and pesticides. Table A4 highlights, by herd-size class, means of variables used to estimate the production technology and the subsequent TFP decomposition for conventional dairy operations.

Table A4

Means of variables used in analysis of conventional dairy operations by herd-size class, 2000–2016

Variables	1,000+	501–999	251–500	101–250	1–100
Milk (cwt)	458,522.60	147,108.80	71,179.09	27,706.35	8,520.57
Milk cows	2,157.58	688.27	361.37	158.22	56.00
Feed (tons)	3,099,504.00	1,800,000.00	437,337.70	199,924.80	72,730.98
Labor (hours)	81,029.88	23,879.52	15,363.44	8,789.05	4,941.82
Capital (thousand dollars, 2020 real)	573.14	283.96	134.91	61.52	20.74
Intermediate (thousand dollars, 2020 real)	7,003.05	3,048.36	1,569.70	688.95	237.29
Optimal thermal days (cows)	4,013.12	3,361.82	3,158.51	3,044.76	2,653.71
Harmful degree-days (cows)	146.54	121.84	113.78	108.91	95.57
Growing degree-days (crops)	3,269.61	3,012.78	2,933.93	2,931.35	2,701.02
Harmful degree-days (crops)	75.44	54.32	44.63	37.33	24.92
Precipitation (millimeters)	388.24	464.90	535.81	606.84	605.45

Notes: Additional descriptive statistics have been suppressed to maintain confidentiality. Intermediate inputs comprise expenses on veterinary, electricity and fuel, fertilizers, and pesticides.

Source: USDA, Economic Research Service using data from the USDA, Economic Research Service and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data for the years 2000, 2005, 2010, and 2016, and weather data from the Parameter-elevation Regressions on Independent Slopes Model Climate Group.

Table A5 highlights variables used for estimation and analysis of organic dairy operations.

Table A5

Means of variables used in analysis of organic dairy operations, 2000–2016

Variables	Mean
Milk (cwt)	12,615.54
Milk cows	90.60
Feed (tons)	138,958.40
Labor (hours)	6,489.98
Capital (thousand dollars, 2020 real)	17.22
Intermediate (thousand dollars, 2020 real)	331.39
Optimal thermal days (cows)	2,279.88
Harmful degree-days (cows)	83.16
Growing degree days (crops)	2,420.44
Harmful degree-days (crops)	12.49
Precipitation (millimeters)	582.20

Notes: Additional descriptive statistics have been suppressed to maintain confidentiality. Intermediate inputs comprise expenses on veterinary, electricity and fuel, fertilizers, and pesticides.

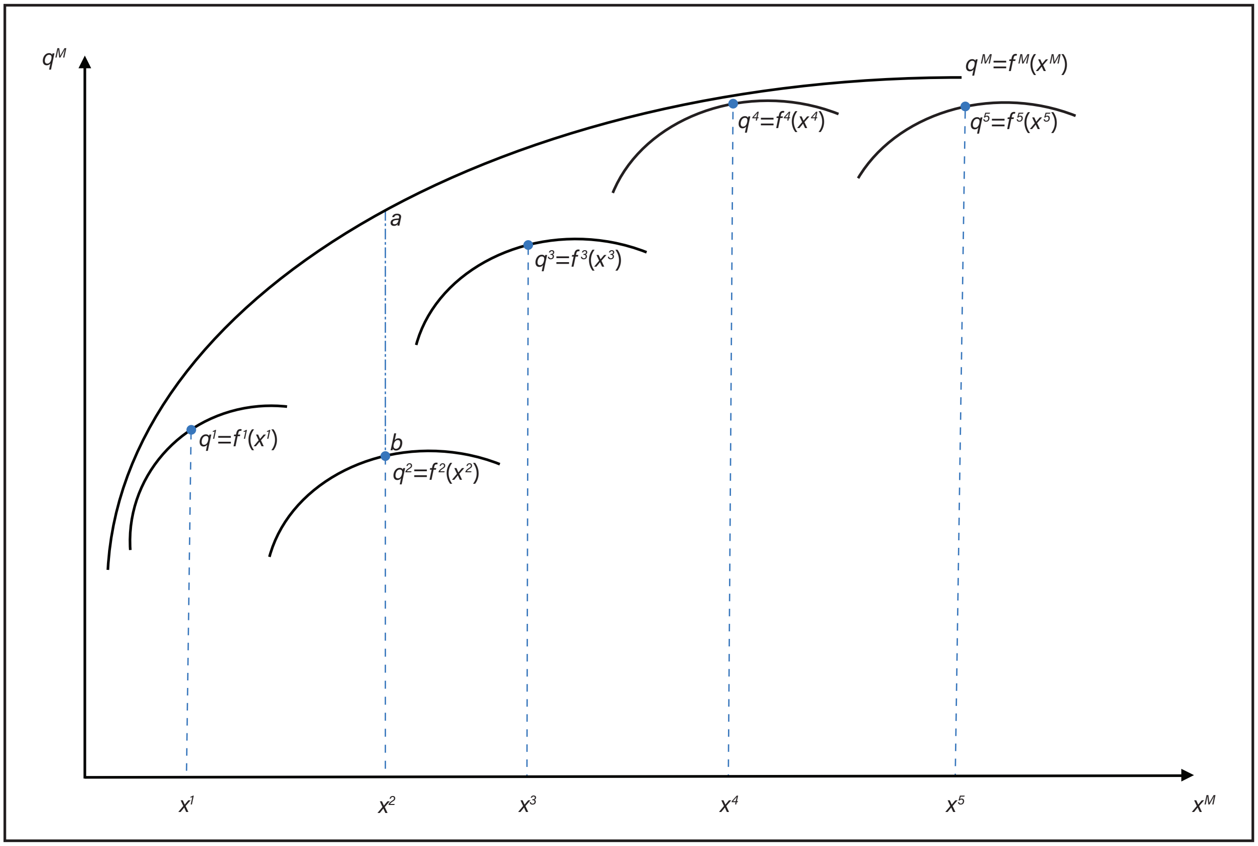
Source: USDA, Economic Research Service using data from the USDA, Economic Research Service and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data for the years 2000, 2005, 2010, and 2016, and weather data from the Parameter-elevation Regressions on Independent Slopes Model Climate Group.

Appendix B: Econometric Approach Used in this Report

This analysis applies a Metaproduction frontier approach. Introduced by Hayami and Ruttan (1971), the Metaproduction frontier conjectures an array of production technologies. Producers select into one of these production technologies based on a set of specific circumstances ranging from firm size, access to productive inputs, physical characteristics of the production environment, to statutory regulations, among others. A graphic illustration is provided in figure B1. In this illustration, there is a common overlaying Metaproduction frontier represented by $q^M = f^M(x^M)$, which envelops five group frontiers, $q^1 = f^1(x^1)$, $q^2 = f^2(x^2)$, $q^3 = f^3(x^3)$, $q^4 = f^4(x^4)$ and $q^5 = f^5(x^5)$. The group frontiers represent the production technologies of five different sets of farms. The variable q, represents milk output, and $f = (.)$ is a function which measures the x aggregate inputs—milk cows, feed, capital, labor hours, intermediate materials, such as veterinary services, fuel, and fertilizer used by the dairy operation.

Figure B1

A Metaproduction frontier model



Source: USDA, Economic Research Service

In this study, the individual group production technologies are based on herd-size class. The rationale being that dairy operations use a specific set of management practices based on how many milk cows they have. For example, it is more cost-effective for large dairy operations to use total mix rations (TMR) feeding systems, whereas smaller herd sizes can get by with lower-cost component feeding systems and management-intensive feeding systems. In addition, information technology systems, capital, and machinery are likely to be more sophisticated in larger herd-size classes than in smaller ones. Moreover, large farms may be subject to additional regulations such as concentrated animal feeding operation (CAFO) standards, which stipulate how manure and wastewater are discharged from such operations. Five herd-size classes are estimated in this analysis, they are: (1) 1–100 cows; (2) 101–250; (3) 251–500; (4) 501–999; and (5) 1,000 and greater.

The set of all input-output combinations satisfy the properties of a regular technology, including:

- producing zero outputs is permissible (i.e., inactivity is possible);
- limiting what can be produced using a given input-vector (i.e., inputs are bounded);
- requiring a strictly positive amount of at least one input to generate a positive amount of output (i.e., inputs are weakly essential);
- using a set of inputs to produce a given output vector, which then can also be used to produce a scalar contraction of that output vector (i.e., outputs are weakly disposable);
- producing a particular set of outputs using a given input vector, which can then also be produced using a scalar magnification of that input vector (i.e., inputs are weakly disposable); and
- producing a set of outputs using a given input vector that contains all the points on its boundary (i.e., the output set is closed).

Following Huang et al. (2014), the first step in estimating metaproduction function involves estimating each of the *j*-group production frontiers using a stochastic frontier methods, as follows:

$$\ln q^j_{it} = f^j\,(x^j_{it}, z^j_{it}) + v^j_{it} - u^j_{it} \tag{1}$$

Where $\ln q^j_{it}$ is the log of milk output for the *i*-th dairy operation in the *j*-th production group of farms in time period *t*. The function f^j (.) is an approximating function chosen by the researcher to represent the *j*-th production group and represents each of the five herd-size classes mentioned before. The conventional inputs, x^j_{it}, include milk cows, homegrown and purchased feed, capital (proxied using interest rates paid, depreciation expenses, and rental and lease), labor hours, intermediate materials (comprising expenditures on veterinary, fuel and electricity, fertilizer, and pesticides), and environmental variables, z^j_{it}, which includes–growing degree-days for crops (GDD), optimal thermal days for cows (OTD), harmful degree-days for crops (HDD-crops), and harmful degree-days for cows (HDD-cows). The term, v^j_{it} captures statistical noise, and u^j_{it}, is a term that measures technical efficiency (TE), which represents the distance of the *i*-th dairy operation from the *j*-th group production frontier. The components v^j_{it} and u^j_{it} take on distributional properties $v_{it} \sim N(0,\sigma^2_v)$ and $u_{it} \sim N^+(0,\sigma^2_u)$, respectively. The functional form specification for each *j*-th group is given as:[21]

$$\ln q^j_{it} = \phi_i + \gamma_t t + \sum_{m=1}^{M} \beta_m \ln x^j_{mit} + \sum_{n=1}^{N} \rho_n \ln z^j_{nit} + v^j_{it} - u^j_{it} \tag{2}$$

Where $\ln q^j_{it}$, $\ln x^j_{mit}$, v^j_{it}, and u^j_{it} are as defined above. The parameters ϕ_i and γ_t measure State-level and time fixed effects, respectively, and β_m and ρ_k are parameters to be estimated. Equation 2 above is estimated using maximum likelihood methods.

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[21] Zellner et al. (1966) argue that when the production process is not instantaneous, the effect on output remains unknown until after the preselected input quantities have been employed, thus resulting in an uncertain quantity of output. The implication is that the maximum likelihood estimates are independent of the disturbance term, hence identified. Notwithstanding, challenges to identification may remain. The first, reverse-causality or simultaneity, may result when inefficiency influences some elements of productivity. However, this is only plausible if producers know their inefficiency levels before embarking on production. The second identification challenge, self-selection, emerges when the choice of input-mix by farms is driven by size considerations. We expect larger farms to be more technologically adept than their smaller counterparts. These patterns imply a productivity dispersion from smaller farms to larger farms (Olley and Pakes, 1996). We try to address that here by using metaproduction frontiers. The third identification challenge relates to unobserved confounders that are correlated with the error term—largely due to omitted variables that comprise all production-related activities not captured in the surveys. We try to capture most of them here by including temporal (year) effects and spatial (State-level) fixed effects.

The estimates from all the *j*-th group frontiers are then used to estimate the overlaying stochastic metafrontier, which is expressed as follows:

$$\ln f^{j}\,(x_{it}^{j}, z_{it}^{j}) = \ln f^{M}\,(x_{jit}^{M}, z_{jit}^{M}\,) + v_{jit}^{M} - u_{jit}^{M} \tag{3}$$

Here, $\exp(u_{it}^{M}) = f^{j}\,(x_{it}^{j}, z_{it}^{j}) / (f^{M}\,(x_{jit}^{M}, z_{jit}^{M})\exp\,(v_{jit}^{M}) \leq 1$ is the technology gap ratio (TGR), defined as the distance from the *j*-th group production frontier to the metafrontier. Finally, the location or the distance of the i-th dairy operation relative to the metafrontier production technology is referred to as the meta-technical efficiency (MTE), and this is expressed as the product of the farm's individual technical efficiency (TE) and the technological gap ratio (TGR). Equation 3 is also estimated using a maximum likelihood approach.

Growing Degree-Days–Crops

The growing degree-days for crops are calculated by taking the integral of the upper and lower temperature threshold, such that:

$$GDD = \int_{50}^{86}(T(t)\text{-}50)\ \theta(t)dt \tag{4}$$

Where $\theta(t)$ and dt represent a heat accumulation factor over a 24-hour period, respectively. The number of degree-days are summed over the previous year's growing season, April to September, to obtain the cumulative growing degree-days. It is assumed the crop development rate is zero below the lower bound. However, temperatures above the threshold are considered detrimental for crop development and are calculated as harmful degree-days - crops (HDD-crops) by taking the following integral:

$$HDD = \int_{87}^{\infty}(T(t)\text{-}87)\ \theta(t)dt \tag{5}$$

Optimal Thermal Days – Cows

Similarly, the optimal thermal days for cows are calculated by taking the upper and lower temperature threshold for the thermoneutral zone which falls between 41°F and 77°F:

$$OTD = \int_{41}^{77}(T(t)\text{-}41)\ \theta(t)dt \tag{6}$$

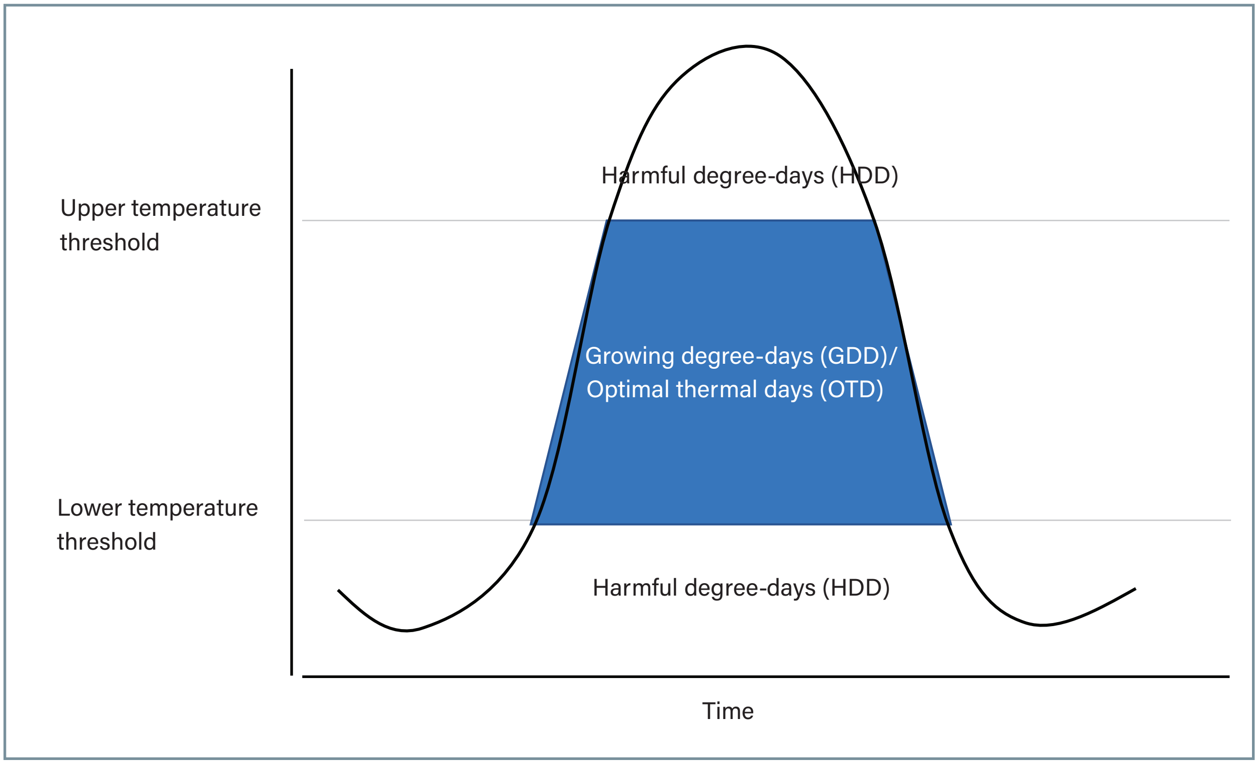
Again, $\theta(t)$ and dt represent a heat accumulation factor over a 24-hour period, respectively. The optimal upper and lower temperature thresholds are where normal heat generated by dairy cows due to milk production, feed intake and nutrient metabolism equals the energy lost to the ambient environment (Roenfeldt, 1998; Kadzere et al., 2002). Temperatures outside of these thresholds have the potential to negatively affect the normal physiological functioning of cows. These are considered harmful degree days for cows (HDD-cows) and are calculated as:

$$HDD = \int_{77}^{\infty}(T(t)\text{-}77)\ \theta(t)dt \tag{7}$$

An illustration of growing degree-days, harmful degree-days, and optimal thermal days is provided in figure B2. Within any 24-hour period, temperatures between the upper and lower temperature thresholds are considered favorable for the cows' well-being and for crop development. On the other hand, temperatures outside of these thresholds are considered unfavorable and potentially harmful for cows' well-being and for crop development.

Figure B2

Calculating growing degree-days, optimal thermal days, and harmful degree-days



Source: USDA, Economic Research Service

The estimated coefficients for the stochastic production frontiers for conventional dairy operations by herd-size class and the stochastic metafrontier are shown in table B1.

Table B1

Estimated coefficients of stochastic metafrontier, and herd-size class specific stochastic production frontiers

		Metafrontier	1,000+	501–999	251–500	101–250	1–100
Parameter/Variable		Coef. (Std. Err)	Coef. (Std. Err)	Coef. (Std. Err)	Coef. (Std. Err)	Coef. (Std. Err)	Coef. (Std. Err)
β_1	Cows	0.7880***	0.7871***	0.9466***	0.9556***	0.7833***	0.7917***
		(0.0024)	(0.0327)	(0.0655)	(0.0515)	(0.0343)	(0.0244)
β_2	Capital	0.1911***	0.2143***	0.2235***	0.1570***	0.2122***	0.2042***
		(0.0017)	(0.0207)	(0.0353)	(0.0222)	(0.0146)	(0.0145)
β_3	Feed	0.0062***	0.0024	0.0001	0.0228***	0.0005	0.0054
		(0.0008)	(0.0083)	(0.0066)	(0.0094)	(0.0071)	(0.0092)
β_4	Labor	0.0296***	0.0230*	0.0134	0.0138	0.0289**	0.0489***
		(0.0015)	(0.0092)	(0.0152)	(0.0145)	(0.0129)	(0.0151)
β_5	Intermediate	0.0724***	0.0506***	0.0607***	0.0393*	0.0507***	0.0871***
		(0.0015)	(0.0166)	(0.0213)	(0.0205)	(0.0105)	(0.0112)
ρ_1	Optimal thermal days - cows	0.7225***	0.0748*	0.5292*	0.5813***	0.4262**	0.7277***
		(0.0266)	(0.0341)	(0.3179)	(0.2330)	(0.2023)	(0.2629)

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		Metafrontier	1,000+	501–999	251–500	101–250	1–100
Parameter/Variable		Coef. (Std. Err)	Coef. (Std. Err)	Coef. (Std. Err)	Coef. (Std. Err)	Coef. (Std. Err)	Coef. (Std. Err)
ρ_2	Harmful degree-days - cows	-0.6867***	-0.2002	-0.4581	-0.5642***	-0.4152**	-0.6012**
		(0.0255)	(0.3048)	(0.2894)	(0.2176)	(0.1954)	(0.2602)
ρ_3	Precipitation	0.2544***	-0.1440	-0.0857	0.2745*	0.4836***	0.5945***
		(0.0143)	(0.1431)	(0.1595)	(0.1538)	(0.1199)	(0.1911)
ρ_4	Precipitation squared	-0.0239***	0.0155	0.0087	-0.0311**	-0.0409***	-0.0499***
		(0.0014)	(0.0154)	(0.0174)	(0.0152)	(0.0109)	(0.0158)
ρ_5	Growing degree-days - crops	0.1098***.	0.5936***	0.153	0.1104	0.1458	-0.1472
		(0.0129)	(0.1850)	(0.1650)	(0.1151)	(0.0994)	(0.1259)
ρ_6	Harmful degree-days - crops	-0.0019***	-0.0038	-0.0100*	-0.0022	-0.0053	0.0040
		(0.0005)	(0.0069)	(0.0061)	(0.0053)	(0.0042)	(0.0040)
γ_1	Trend	0.0218***	0.0276***	0.0136***	0.0125***	0.0260***	0.0208***
		(0.0008)	(0.0128)	(0.0011)	(0.0008)	(0.0061)	(0.0063)
γ_{11}	Trend squared	0.0007***	0.0006	0.0012***	0.0007*	0.0007***	0.0007***
		(0.0000)	(0.0006)	(0.0006)	(0.0004)	(0.0003)	(0.0003)
ϕ_i	State-level fixed effects	yes	yes	yes	yes	yes	yes
σ_v	Sigma(v)	0.0443***	0.0627***	0.0997***	0.0772***	0.1272***	0.1923***
		(0.0011)	(0.0136)	(0.0169)	(0.0116)	(0.0088)	(0.0081)
σ_u	Sigma(u)	0.0656***	0.3800***	0.2985***	0.3547***	0.3575***	0.4320***
		(0.0023)	(0.0199)	(0.0251)	(0.0174)	(0.0145)	(0.0144)
λ	lambda	1.4823***	6.0566***	2.9945***	4.5943***	2.8102***	2.2469***
		(0.0033)	(0.0295)	(0.0395)	(0.0258)	(0.0210)	(0.0202)
	Log likelihood	5644.07	40.21	71.74	66.00	50.37	75.13

Notes: Coeff. = coefficient. Std. Err. = standard error. ***, **, * indicate statistical significance at the 1, 5, and 10 percent levels. The variables are as defined in table A5. Intermediate inputs comprise expenses on veterinary, electricity and fuel, fertilizers, and pesticides. The parameters β_m, ρ_n, γ_t, and ϕ_i represent coefficient estimates for the conventional input variables, weather variables, time-trend, and State-level fixed effects, respectively. The parameters, σ_u and σ_v, where $\lambda=\sigma_u/\sigma_v$ measures the relative contribution of the share of *u* and *v* to the total composed error term.

Source: USDA, Economic Research Service using data from the USDA, Economic Research Service and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data for the years 2000, 2005, 2010, and 2016, and weather data from the Parameter-elevation Regressions on Independent Slopes Model Climate Group.

The estimates of β_m, and ρ_n, parameters (i.e., estimates of the coefficient for the conventional inputs and environmental variables) can be interpreted as average elasticities. For example, for the largest herd-size class with 1,000+ cows, a 1-percent increase in the number of milk cows results in a 0.787-percent increase in milk output. Similarly, a 1-percent increase in the number of optimal thermal days (OTD) results in a 0.07-percent increase in milk output. Furthermore, the estimate for the time trend, γ_1, indicates technological progress contributes at least a 2.76-percent increase in milk output annually. These estimates are subsequently used as weights to construct and decompose total factor productivity index (TFPI) and its components. The estimates of σ_u and σ_v, where $\lambda=\sigma_u/\sigma_v$, measures the relative contribution of the share of u and v to the total composed error term.[22] Average technical efficiency estimates, which measures where the average farm operates relative to its group frontier or how efficiently dairy operations combine various inputs in order to maximize output relative to other farms in their group, are provided in table B2.

Table B2

Average technical efficiency estimates by herd-size class

Herd-size class	Mean	Standard deviation	Minimum	Maximum
1,000+	0.7765	0.1437	0.1291	0.9803
501–999	0.8033	0.1167	0.2898	0.9742
251–500	0.7810	0.1370	0.1067	0.9751
101–250	0.7737	0.1275	0.1417	0.9775
1–100	0.7377	0.1339	0.1151	0.9770

Source: USDA, Economic Research Service using data from the USDA, Economic Research Service and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data for the years 2000, 2005, 2010, and 2016.

The results can be interpreted as follows. The technical efficiency for the average dairy operation in the 1,000+ and 501–999 herd-size classes was 77.65 and 80.33 percent, respectively. If the distance from the frontier were measured on a scale from 0 to 100, one may conclude the average farm in the 1,000+ category was 22.35 points away from the frontier (calculated as 100–77.65), and the average farm in the 501–999 herd-size class operated approximately 19.67 points from the frontier. In addition, the distance of the individual group frontiers relative to the metaproduction frontier is shown in table B3. This is referred to as the technology gap ratio.

Table B3

Average technology gap ratio by herd-size class

Herd-size class	Mean	Standard deviation	Minimum	Maximum
1,000+	0.9348	0.0472	0.3741	0.9909
501–999	0.9444	0.0306	0.8417	0.9948
251–500	0.9547	0.0261	0.8086	0.9920
101–250	0.9482	0.0226	0.7020	0.9845
1–100	0.9562	0.0165	0.7956	0.9826

Source: USDA, Economic Research Service using data from the USDA, Economic Research Service and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data for the years 2000, 2005, 2010, and 2016.

Finally, the meta-technical efficiency estimates, which measure the distance of the average farm from the stochastic metafrontier, are shown in table B4.

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[22] The interested reader is directed to Kumbhakar and Lovell (2000, chapter 3) for an in-depth analysis of stochastic production frontier estimation.

Table B4

Average meta-technical efficiency estimates by herd-size class

Herd-size class	Mean	Standard deviation	Minimum	Maximum
1,000+	0.7247	0.1353	0.1219	0.9582
501–999	0.7587	0.1132	0.2600	0.9510
251–500	0.7455	0.1315	0.0997	0.9511
101–250	0.7335	0.1218	0.1376	0.9368
1–100	0.7055	0.1289	0.1111	0.9223

Source: USDA, Economic Research Service using data from the USDA, Economic Research Service and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data for the years 2000, 2005, 2010, and 2016.

This can be interpreted as the average technical efficiency of the dairy operation based on the stochastic metafrontier. For example, on a scale of 0 to 100, we conclude the average dairy operation in the 1,000+ herd-size class was 27.53 points away from the stochastic metafrontier (calculated as 100–72.47).

Finally, the estimated coefficients for the stochastic production frontier model for organic dairy operations is shown in Table B5.

Table B5

Estimated coefficients for the stochastic production frontier model for organic dairy operations

Parameter/Variable		Coefficient	(Standard error)
β_1	Cows	0.6230***	(0.0375)
β_2	Capital	0.3340***	(0.0315)
β_3	Feed	0.0126**	(0.0058)
β_4	Labor	0.0681***	(0.01847)
β_5	Intermediate	0.0560***	(0.0164)
ρ_1	Optimal thermal days - cows	0.0001	(0.0001)
ρ_2	Harmful degree-days - cows	-0.0021	(0.0035)
ρ_3	Precipitation	0.0001	(0.0001)
ρ_4	Growing degree-days - crops	0.0001	(0.0001)
ρ_5	Harmful degree-days - crops	-0.0011	(0.0016)
γ_1	Trend	0.3274***	(0.0334)
γ_2	Trend squared	-0.0208***	(0.0022)
ϕ_i	State-level fixed effects	yes	
σ_v	Sigma(v)	0.1769***	(0.0164)
σ_u	Sigma(u)	0.3291***	(0.0258)
λ	lambda	1.8597***	(0.0402)
	Log likelihood	86.14	

Notes: ***, **, * indicate statistical significance at the 1, 5, and 10 percent levels. The variables are as defined in table A5. Intermediate inputs comprise expenses on veterinary, electricity and fuel. The parameters β_m, ρ_n, γ_t, and ϕ_i represent coefficient estimates for the conventional input variables, weather variables, and State-level fixed effects, respectively. The parameters, σ_u and σ_v, where $\lambda=\sigma_u/\sigma_v$ measures the relative contribution of the share of *u* and *v* to the total composed error term.

Source: USDA, Economic Research Service using data from the USDA, Economic Research Service and USDA, National Agricultural Statistics Service, Agricultural Resource Management Survey data for the years 2000, 2005, 2010, and 2016 and weather data from the Parameter-elevation Regressions on Independent Slopes Model Climate Group.

Like the results above, the estimates of β_m, and ρ_n, parameters can be interpreted as average elasticities. These results reveal, on average, a 1-percent increase in the number of milk cows resulted in a 0.62-percent increase in milk output, and a 1-percent increase in capital resulted in a 0.33-percent increase in milk output. The estimates for weather variables are not statistically significant.

Appendix C: Calculating and Decomposing Total Factor Productivity (TFP) Index

Total factor productivity (TFP) measures the rate of change in aggregate output relative to the rate of change in aggregate inputs. A TFP index comparing the productivity of a firm *i* in period *t* with the productivity of firm *k* in period *s* is any variable of the form $TFPI(x_{ks}, q_{ks}, x_{it}, q_{it}) = [Q(q_{it})/X(x_{it})]/[Q(q_{ks})/X(x_{ks})]$. The multiplicative index used in this study takes the following form (O'Donnell, 2018):

$$TFPI^{M}(x_{ks}, q_{ks}, x_{it}, q_{it}) = \frac{q_{it}}{q_{ks}} \prod_{m=1}^{M} \left(\frac{x_{mks}}{x_{mit}}\right)^{b_m} \tag{8}$$

whereby $b_m = \hat{\beta}_m / \sum_{k=1}^{M} \hat{\beta}_k$ and $\hat{\beta}_m$ is an estimator of β_m and represents a nonnegative input weight that sums to one. Recall the stochastic production frontier model in equation 2 in appendix B:

$$\ln q_{it} = \phi_i + \gamma_t + \sum_{m=1}^{M} \beta_m \ln x_{mit} + \sum_{n=1}^{N} \rho_n \ln z_{nit} + v_{it} - u_{it}$$

The TFP can be restated by taking the antilogarithm to obtain:

$$q_{it} = \exp(\phi_i)\exp(\gamma_t)\left[\prod_{m=1}^{M} x_{mit}^{\beta_m}\right]\left[\prod_{n=1}^{N} z_{nit}^{\rho_n}\right]\exp(v_{it})\exp(-u_{it}) \tag{9}$$

And substituting q_{it} and q_{ks} out of equation 8, where the subscripts *it* and *ks* represent the comparison and reference vectors, respectively, we obtain the TFP index that compares productivity of farm *i* in period *t* with the productivity of farm *k* in period *s*.

$$\begin{aligned} &TFPI^{M}(x_{ks}, q_{ks}, x_{it}, q_{it}) \\ &= \left[\frac{exp(\gamma_t t)}{exp(\gamma_s s)}\right] \times \left[\left(\frac{exp(\phi_i)}{exp(\phi_k)}\right)\prod_{n=1}^{N}\left(\frac{z_{nit}^{\rho_n}}{z_{nks}^{\rho_n}}\right)\right] \\ &\times \left[\prod_{m=1}^{M}\left(\frac{x_{mit}^{\beta_m}}{x_{mks}^{\beta_m}}\right)\right] \times \left[\frac{exp(u_{it})}{exp(u_{ks})}\right] \times \left[\frac{exp(v_{it})}{exp(v_{ks})}\right] \end{aligned} \tag{10}$$

Where the first component in brackets on the right-hand side measures technological progress, the second component measures environmental change, the third component measures scale-and-mix efficiency, the fourth component measures technical efficiency change, and the last component measures statistical noise. The results of the TFPI decomposition are provided in table 2 under the section, Trends in Total Factor Productivity Growth. An illustration of how TFP change is calculated is shown below where average TFPI and its components for various States are indicated in table B5.

Table B5

Average TFPI and its components for Arizona, California, Idaho, and Tennessee by year, 2000–16

State	Year	TFPI	TPI	SMEI	TEI	EI-feed	EI-cows
Arizona	2000	1.1206	0.9926	0.9509	1.0309	1.1277	1.0048
Arizona	2016	2.0900	1.7961	0.9917	0.9289	0.9927	0.9747
California	2016	1.9510	1.7450	0.9702	0.8173	0.9659	0.9748
Idaho	2016	2.2328	1.7466	0.9495	0.9072	1.2284	0.9715
Tennessee	2016	1.2931	1.7352	0.8056	0.8365	1.6582	0.9630

Notes: TFPI=total factor productivity index. TPI=technological progress index. TEI= technological efficiency index. SMEI=scale-and-mix efficiency index. EI=environmental index. TFPI is the product of its components: TI, SMEI, TEI, EI-feed, EI-cows, and a statistical noise index (SNI). For example, TFPI for Arizona in 2000 is given as 1.1206=0.9926×0.9509×1.0309×1.1277×1.0048×1.0164.

Source: USDA, Economic Research Service using Agricultural Resource Management Survey data.

Using the TFPI from Arizona in the year 2000 as the base year, TFP percent change (TFPI) in Arizona between 2000 and 2016 is calculated as the rate by which it would take to compound 1.1206 in order to arrive at 2.0900, which is$(2.0900/1.1206)^{1/(2016-2000)}$-1=0.03973=3.973 percent. Similarly, the TFP change for California dairy operations relative to the reference farms (Arizona dairy operations in 2000) is obtained using the same method, which is$(1.9510/1.1206)^{1/(2016-2000)}$-1=0.03526=3.5265 percent. Finally, the TFP change for Tennessee dairy farms relative to the reference farms in 2000 is $(1.2931/1.1206)^{1/(2016-2000)}$-1=0.00899=0.899 percent. These are the numbers provided in table 2 under the section, Trends in Total Factor Productivity Growth.