## Supplementary Materials—Tables

Table S1. Global Simulation Locations

| | Coordinates and Elevation | | |
|---|---|---|---|
| Location | Latitude | Longitude | Elevation (m) |
| Philippines | 12.03 | 123.77 | 27.72 |
| China | 30.02 | 114.32 | 27 |
| Russia | 60.14 | 166.33 | 22.56 |
| Nicaragua | 12.18 | -84.28 | 21.03 |
| Texas, USA | 30.12 | -94.68 | 23.52 |
| Canada | 60.11 | -95.04 | 36 |

Tables S2. Average monthly climate data for 6 simulation locations

| Month | Max. Temp °C | Min. Temp °C | Max. Rel. Humid % | Min. Rel. Humid % | Wind Speed (10 m) m/s | Cloud Cover % | Rainfall mm/mo |
|---|---|---|---|---|---|---|---|
| Jan | 29.4 | 21.0 | 81.2 | 60.2 | 2.6 | 45.6 | 55.5 |
| Feb | 30.0 | 21.0 | 80.7 | 57.7 | 2.5 | 39.5 | 26.6 |
| Mar | 31.4 | 22.0 | 78.2 | 55.5 | 2.4 | 33.8 | 30.8 |
| Apr | 32.3 | 22.9 | 100.0 | 53.4 | 2.4 | 30.7 | 61.5 |
| May | 32.2 | 23.0 | 100.0 | 56.9 | 2.0 | 41.5 | 167.9 |
| Jun | 30.6 | 22.4 | 100.0 | 62.3 | 2.1 | 52.2 | 266.4 |
| Jul | 29.9 | 22.1 | 100.0 | 65.5 | 2.2 | 57.5 | 324.4 |
| Aug | 29.7 | 22.1 | 100.0 | 66.1 | 2.3 | 58.8 | 344.1 |
| Sep | 30.1 | 22.1 | 100.0 | 65.1 | 1.9 | 54.1 | 286.7 |
| Oct | 30.1 | 22.1 | 100.0 | 64.1 | 2.2 | 47.9 | 300.0 |
| Nov | 30.2 | 22.0 | 100.0 | 62.0 | 2.3 | 45.8 | 191.8 |
| Dec | 29.6 | 21.4 | 100.0 | 60.4 | 2.6 | 49.1 | 119.9 |
| AVE | 30.5 | 22.0 | 95.0 | 60.8 | 2.3 | 46.4 | 181.3 |

Table S2a. Philippine site climate. Data for all sites from (New et al., 2002)

| Month | Max. Temp °C | Min. Temp °C | Max. Rel. Humid % | Min. Rel. Humid % | Wind Speed (10m) m/s | Cloud Cover % | Rainfall mm/mo |
|---|---|---|---|---|---|---|---|
| Jan | 8.3 | -0.5 | 100.0 | 55.5 | 2.5 | 61.7 | 35.4 |
| Feb | 9.8 | 1.4 | 100.0 | 57.6 | 2.7 | 65.4 | 58.4 |
| Mar | 14.8 | 6.1 | 100.0 | 59.4 | 2.7 | 67.0 | 95.1 |
| Apr | 21.1 | 12.2 | 100.0 | 58.2 | 2.6 | 62.5 | 140.6 |
| May | 26.4 | 17.6 | 100.0 | 58.1 | 2.4 | 58.1 | 163.1 |
| Jun | 29.9 | 21.8 | 100.0 | 60.1 | 2.3 | 55.0 | 210.1 |
| Jul | 33.0 | 25.2 | 100.0 | 61.5 | 2.6 | 43.3 | 161.1 |
| Aug | 33.0 | 24.6 | 100.0 | 59.7 | 2.4 | 38.0 | 124.7 |
| Sep | 28.0 | 19.4 | 100.0 | 58.9 | 2.5 | 51.4 | 84.1 |
| Oct | 22.8 | 13.4 | 100.0 | 56.7 | 2.3 | 53.9 | 84.7 |
| Nov | 16.5 | 7.2 | 100.0 | 54.6 | 2.4 | 55.1 | 58.2 |
| Dec | 10.6 | 1.4 | 100.0 | 51.7 | 2.4 | 56.0 | 29.2 |
| AVE | 21.2 | 12.5 | 100.0 | 57.7 | 2.5 | 55.6 | 103.7 |

Table S2b. China site climate

| Month | Max. Temp | Min. Temp | Max. Rel. Humid | Min. Rel. Humid | Wind Speed (10m) | Cloud Cover | Rainfall |
|---|---|---|---|---|---|---|---|
| | °C | °C | % | % | m/s | % | mm/mo |
| Jan | -11.1 | -18.0 | 100.0 | 70.7 | 6.7 | 72.2 | 33.9 |
| Feb | -10.9 | -18.0 | 100.0 | 70.9 | 6.8 | 60.4 | 26.9 |
| Mar | -9.1 | -16.8 | 100.0 | 66.4 | 5.9 | 49.7 | 23.2 |
| Apr | -4.0 | -11.5 | 100.0 | 62.8 | 4.9 | 51.2 | 23.1 |
| May | 4.3 | -2.1 | 100.0 | 62.5 | 4.0 | 60.4 | 26.4 |
| Jun | 11.2 | 4.2 | 100.0 | 57.9 | 3.9 | 61.0 | 33.6 |
| Jul | 14.4 | 8.1 | 100.0 | 61.9 | 3.9 | 65.5 | 57.6 |
| Aug | 14.2 | 8.1 | 100.0 | 62.9 | 3.8 | 64.9 | 64.1 |
| Sep | 9.9 | 3.6 | 100.0 | 61.5 | 3.8 | 62.5 | 51.5 |
| Oct | 1.2 | -4.6 | 100.0 | 64.7 | 4.7 | 63.2 | 52.3 |
| Nov | -7.4 | -13.7 | 100.0 | 67.7 | 5.9 | 69.1 | 47.7 |
| Dec | -10.9 | -17.8 | 100.0 | 67.7 | 6.6 | 81.6 | 33.5 |
| AVE | 0.2 | -6.5 | 100.0 | 64.8 | 5.1 | 63.5 | 39.5 |

Table S2c. Russia site climate

| Month | Max. Temp | Min. Temp | Max. Rel. Humid | Min. Rel. Humid | Wind Speed (10m) | Cloud Cover | Rainfall |
|---|---|---|---|---|---|---|---|
| | °C | °C | % | % | m/s | % | mm/mo |
| Jan | 29.0 | 21.8 | 82.0 | 65.4 | 4.3 | 51.9 | 171.1 |
| Feb | 30.0 | 21.8 | 80.6 | 61.0 | 4.1 | 43.8 | 94.2 |
| Mar | 31.4 | 22.6 | 79.9 | 59.5 | 4.1 | 41.0 | 49.8 |
| Apr | 31.9 | 23.5 | 99.8 | 56.5 | 4.1 | 41.2 | 62.5 |
| May | 31.1 | 23.5 | 100.0 | 62.7 | 3.4 | 43.5 | 208.7 |
| Jun | 29.8 | 22.6 | 100.0 | 65.5 | 3.2 | 52.2 | 445.2 |
| Jul | 29.9 | 23.1 | 100.0 | 68.4 | 3.5 | 58.4 | 533.0 |
| Aug | 29.6 | 22.5 | 100.0 | 67.0 | 3.2 | 57.8 | 431.1 |
| Sep | 29.1 | 22.0 | 100.0 | 68.0 | 2.7 | 53.4 | 287.8 |
| Oct | 29.3 | 21.9 | 100.0 | 64.0 | 2.7 | 53.9 | 296.1 |
| Nov | 28.7 | 21.5 | 100.0 | 65.5 | 3.3 | 51.7 | 243.0 |
| Dec | 28.6 | 21.4 | 100.0 | 63.0 | 4.0 | 46.5 | 211.6 |
| AVE | 29.9 | 22.4 | 95.2 | 63.9 | 3.6 | 49.6 | 252.8 |

Table S2d. Nicaragua site climate

| Month | Max. Temp | Min. Temp | Max. Rel. Humid | Min. Rel. Humid | Wind Speed (10m) | Cloud Cover | Rainfall |
|---|---|---|---|---|---|---|---|
| | °C | °C | % | % | m/s | % | mm/mo |
| Jan | 15.8 | 5.4 | 100.0 | 54.6 | 4.5 | 56.1 | 99.7 |
| Feb | 18.1 | 7.2 | 100.0 | 52.6 | 4.7 | 48.3 | 95.1 |
| Mar | 22.0 | 10.6 | 97.4 | 51.8 | 4.9 | 47.4 | 84.2 |
| Apr | 25.9 | 15.1 | 100.0 | 51.2 | 4.9 | 45.4 | 81.8 |
| May | 29.4 | 18.6 | 100.0 | 53.3 | 4.4 | 39.2 | 147.4 |
| Jun | 32.5 | 22.0 | 100.0 | 54.0 | 3.9 | 32.0 | 146.0 |
| Jul | 33.9 | 23.1 | 100.0 | 53.7 | 3.4 | 31.6 | 117.5 |
| Aug | 34.2 | 22.9 | 100.0 | 52.8 | 3.2 | 34.1 | 108.2 |
| Sep | 31.5 | 20.4 | 100.0 | 53.4 | 3.6 | 36.4 | 147.5 |
| Oct | 27.5 | 14.5 | 100.0 | 48.2 | 3.7 | 33.9 | 106.3 |
| Nov | 22.4 | 10.6 | 100.0 | 50.3 | 4.2 | 45.0 | 121.7 |
| Dec | 17.9 | 6.8 | 100.0 | 51.5 | 4.3 | 52.7 | 121.8 |
| AVE | 25.9 | 14.8 | 99.8 | 52.3 | 4.1 | 41.8 | 114.8 |

Table S2e. US, Texas site climate

| Month | Max. Temp | Min. Temp | Max. Rel. Humid | Min. Rel. Humid | Wind Speed (10m) | Cloud Cover | Rainfall |
|---|---|---|---|---|---|---|---|
| | °C | °C | % | % | m/s | % | mm/mo |
| Jan | -24.2 | -33.0 | 100.0 | 46.5 | 6.3 | 66.2 | 14.4 |
| Feb | -21.5 | -31.5 | 100.0 | 44.5 | 6.0 | 52.7 | 10.2 |
| Mar | -15.2 | -27.4 | 100.0 | 44.7 | 5.7 | 49.3 | 15.0 |
| Apr | -5.7 | -16.9 | 100.0 | 48.1 | 5.7 | 49.9 | 19.6 |
| May | 3.5 | -6.3 | 100.0 | 56.7 | 5.4 | 60.2 | 26.5 |
| Jun | 12.2 | 1.2 | 100.0 | 54.8 | 5.0 | 56.1 | 38.7 |
| Jul | 18.4 | 6.8 | 100.0 | 52.4 | 4.8 | 49.5 | 50.2 |
| Aug | 16.5 | 6.6 | 100.0 | 57.2 | 4.9 | 53.0 | 55.6 |
| Sep | 9.8 | 1.8 | 100.0 | 62.6 | 5.6 | 73.0 | 49.6 |
| Oct | 0.2 | -6.3 | 100.0 | 64.4 | 6.1 | 80.1 | 42.5 |
| Nov | -11.4 | -19.5 | 100.0 | 55.2 | 6.1 | 75.6 | 29.6 |
| Dec | -20.5 | -28.6 | 100.0 | 48.7 | 5.7 | 77.2 | 16.7 |
| AVE | -3.2 | -12.8 | 100.0 | 53.0 | 5.6 | 61.9 | 30.7 |

Table S2f. Canada site climate

Table S3. Cow diet categories and properties (NRC Table 15-1)

| Category | | % dry matter | % protein | % fat | % carb, NDF + starch |
|---|---|---|---|---|---|
| | | % as is | %DM | %DM | %DM |
| High Protein Forage (HPF) | Alfalfa-legumes -hay | | | | |
| | Alfa hay pre bloom | 90.0 | 20.0 | 3.8 | 42.0 |
| | Alfa hay mid bloom | 90.0 | 17.0 | 2.6 | 47.8 |
| | Alfa hay full bloom | 90.0 | 15.0 | 2.0 | 51.8 |
| | Category Average | 90.0 | 17.3 | 2.8 | 47.2 |
| | Young grasses | | | | |
| | Grass, pasture early | 27.0 | 19.5 | 4.0 | 55.5 |
| | Grass, pasture late | 45.0 | 9.0 | 2.8 | 70.0 |
| | Grass hay mature | 89.0 | 10.0 | 2.3 | 72.0 |
| | Category Average | 53.7 | 12.8 | 3.0 | 65.8 |
| | Young cereal crops (wheat, barley, oats) | | | | |
| | Barley grain | 88.0 | 12.9 | 2.1 | 76.9 |
| | Oat grain | 89.0 | 11.7 | 5.4 | 74.4 |
| | Wheat grain | 89.0 | 12.0 | 1.9 | 78.3 |
| | Category Average | 88.7 | 12.3 | 3.8 | 75.7 |
| Overall Average | | 77.5 | 14.1 | 3.0 | 63.2 |
| | | | | | |
| High Protein Grains and Byproducts (HPG) | Soybean meal 48% | 89.0 | 55.0 | 1.0 | 16.0 |
| | Canola seed | 90.0 | 20.5 | 40.5 | 17.8 |
| | Meat meal | 94.0 | 60.0 | 9.7 | 0.0 |
| | Fish meal | 92.0 | 67.7 | 10.5 | 0.0 |
| | Cottonseed meal | 91.0 | 45.6 | 1.3 | 28.5 |
| Overall Average | | 91.2 | 49.8 | 12.6 | 12.5 |
| | | | | | |
| High Energy-Low Protein Forage (HEF) | | | | | |
| | Corn silage 10% grain | 35.0 | 9.0 | 3.0 | 71.0 |
| | Sorghum silage | 28.0 | 10.2 | 3.0 | 66.1 |

| | | % as is | % protein | % fat | % carb, NDF+starch |
|---|---|---|---|---|---|
| Overall Average | | 31.5 | 9.6 | 3.0 | 68.6 |

| High Energy-Low Protein Grains | | % as is | % protein | % fat | % carb, NDF+starch |
|---|---|---|---|---|---|
| (HEG) | Corn grain, cracked | 88.0 | 9.3 | 4.3 | 79.5 |
| | Milo (grain sorghum) | 87.0 | 9.7 | 3.4 | 81.4 |
| | Barley grain | 88.0 | 12.9 | 2.1 | 76.9 |
| | Oat grain | 89.0 | 11.7 | 5.4 | 74.4 |
| | Wheat grain | 89.0 | 12.0 | 1.9 | 78.3 |
| Overall Average | | 88.0 | 10.9 | 3.8 | 78.1 |
| | | | | | |
| Medium Protein-Fiber Forage | | | | | |
| (MPF) | Mature cereal crops with grain in milky stage | | | | |
| | Barley silage, headed | 35.5 | 12.0 | 3.5 | 56.3 |
| | Oat hay, headed | 91.9 | 9.1 | 2.2 | 58.0 |
| | Wheat hay, headed | 86.8 | 9.4 | 1.7 | 61.1 |
| Overall Average | | 71.4 | 10.2 | 2.5 | 58.5 |
| | | | | | |
| Medium Protein-Fiber Grains | | | | | |
| (MPG) | Most byproducts | 81.7 | 15.8 | 8.2 | 48.7 |
| | Whole cottonseed | 92.0 | 23.0 | 20.0 | 45.6 |
| | Wheat middlings | 89.0 | 18.4 | 4.9 | 60.3 |
| Overall Average | | 87.6 | 19.1 | 11.0 | 51.5 |

Table S4. Dairy Niche Mapper calculations for a 682 kg Holstein annual diet needs – current and future

| Feed Type - Location | Annual Feed Totals (kg.) | | |
|---|---|---|---|
| | Current | Future | % change |
| Philippines | | | |
| High Protein Forage | 4942 | 3920 | 20.7 |
| High Energy Forage | 4845 | 3843 | 20.7 |
| High Protein Grain | 2782 | 2207 | 20.7 |
| High Energy Grain | 3322 | 2635 | 20.7 |
| Nicaragua | | | |
| High Protein Forage | 5066 | 4453 | 12.1 |
| High Energy Forage | 4967 | 4366 | 12.1 |
| High Protein Grain | 2852 | 2507 | 12.1 |
| High Energy Grain | 3406 | 2994 | 12.1 |
| China | | | |
| High Protein Forage | 5127 | 5062 | 1.3 |
| High Energy Forage | 5027 | 4963 | 1.3 |
| High Protein Grain | 2886 | 2850 | 1.3 |
| High Energy Grain | 3446 | 3403 | 1.3 |
| Texas | | | |
| High Protein Forage | 5119 | 5035 | 1.6 |
| High Energy Forage | 5019 | 4937 | 1.6 |
| High Protein Grain | 2882 | 2835 | 1.6 |
| High Energy Grain | 3453 | 3385 | 2.0 |

| | | | |
|---|---|---|---|
| Russia | | | |
| High Protein Forage | 5837 | 5535 | 5.2 |
| High Energy Forage | 5723 | 5427 | 5.2 |
| High Protein Grain | 3286 | 3116 | 5.2 |
| High Energy Grain | 3924 | 3721 | 5.2 |
| Canada | | | |
| High Protein Forage | 6521 | 6154 | 5.6 |
| High Energy Forage | 6393 | 6034 | 5.6 |
| High Protein Grain | 3671 | 3465 | 5.6 |
| High Energy Grain | 4383 | 4137 | 5.6 |

Table S5. Yates algorithm analysis of DNM results for latitude, body size and diet effects. Interactions, e.g., 1x2 is latitude x body size interaction. 5 September calving.

| Effects on Current Annual Milk | | |
|---|---|---|
| Holsteins:: | N. America., kg | Holsteins: Asia, kg |
| 1) Latitude | 361. | 850. |
| 2) Body size | -317. | -662. |
| 3) Diet | 0. | 0. |
| 1x2 | 317. | 662. |
| 1x3 | 0. | 0. |
| 2x3 | 0. | 0. |
| 1x2x3 | 0. | 0. |
| **Effects on Future Annual Milk** | | |
| Holsteins: | N. America., kg | Holsteins: Asia, kg |
| 1) Latitude | 2712. | 4944. |
| 2) Body size | -1798. | -2692. |
| 3) Diet | 0 | 0 |
| 1x2 | 1798. | 2692. |
| 1x3 | 0 | 0 |
| 2x3 | 0 | 0 |
| 1x2x3 | 0 | 0 |
| **Effects on Current Annual Water** | | |
| Holsteins:: | N. America., kg | Holsteins: Asia, kg |
| 1) Latitude | -2334. | -3240. |
| 2) Body size | 2989. | 2658. |
| 3) Diet | -3754. | -3457. |
| 1x2 | -1407. | -1405. |
| 1x3 | -497. | -326. |
| 2x3 | -566. | -461. |
| 1x2x3 | -78. | -48. |
| **Effects on Future Annual Water** | | |
| Holsteins:: | N. America., kg | Holsteins: Asia, kg |
| 1) Latitude | -1846. | -178. |
| 2) Body size | 1462. | 505. |
| 3) Diet | -3377. | -2995. |
| 1x2 | 53. | 763. |
| 1x3 | -640. | -605. |
| 2x3 | -403. | -292. |
| 1x2x3 | -206. | -214. |

**Supplementary Material - Figures**

Figure S1. Simulation locations for North America and Asia for the Yates' algorithm analyses of how latitude, bovine body size and diet type can affect feed and water needs and milk production potential in outdoor environments. Table S1 shows the geographic coordinates and elevations.

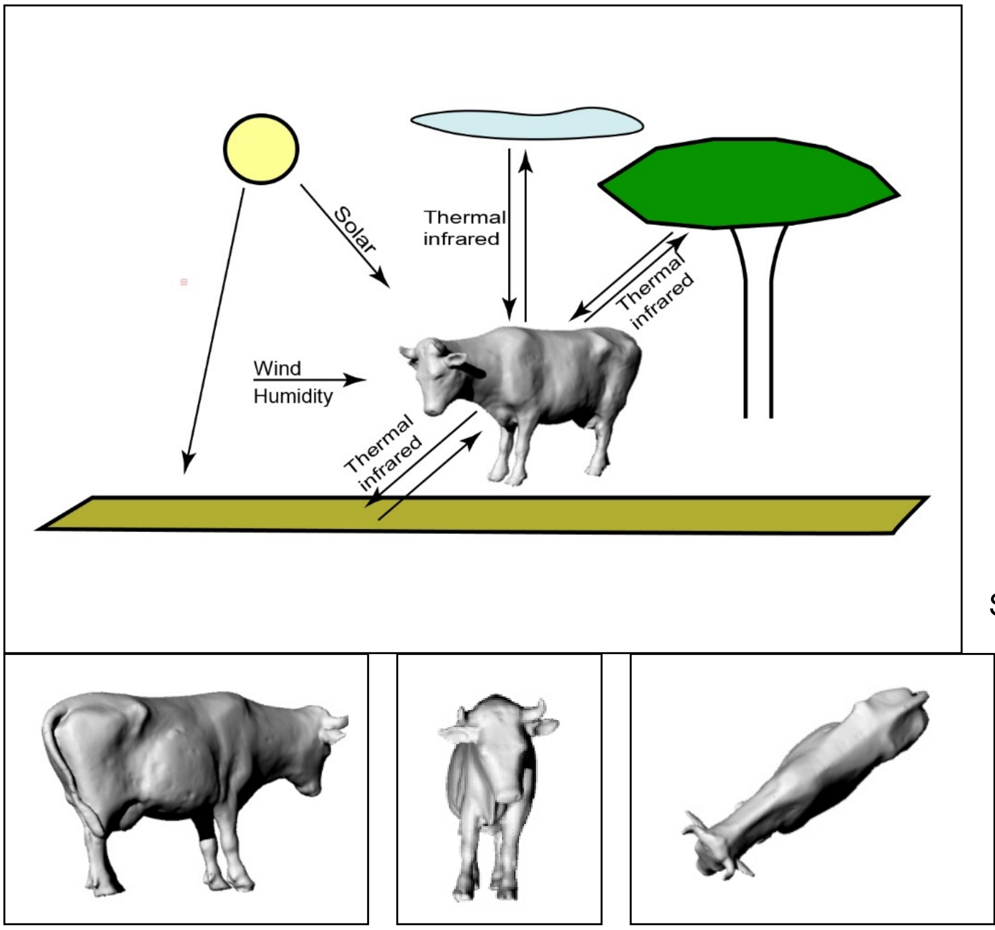



Figure S2a

Figure S2b Figure S2c Figure S2d

Figure S2a. Overview of the heat energy balance on a cow outdoors. The top cow image is an oblique view of the 3D image used to obtain 1) the heat and mass transfer coefficients via ANSYS Fluent as described in Dudley et al.(Dudley et al., 2013), 2) the surface, silhouette areas and volume of the cow for any height and weight. The other three figures, S2b, S2c and S2d, are the side, front and top virtual cow views. Dairy Niche Mapper allows for isometric and non-isometric scaling via user inputs of weight and height of a cow. The program automatically checks for consistency of mass, density and volume and corrects the anatomy isometrically or radially depending on user specifications.

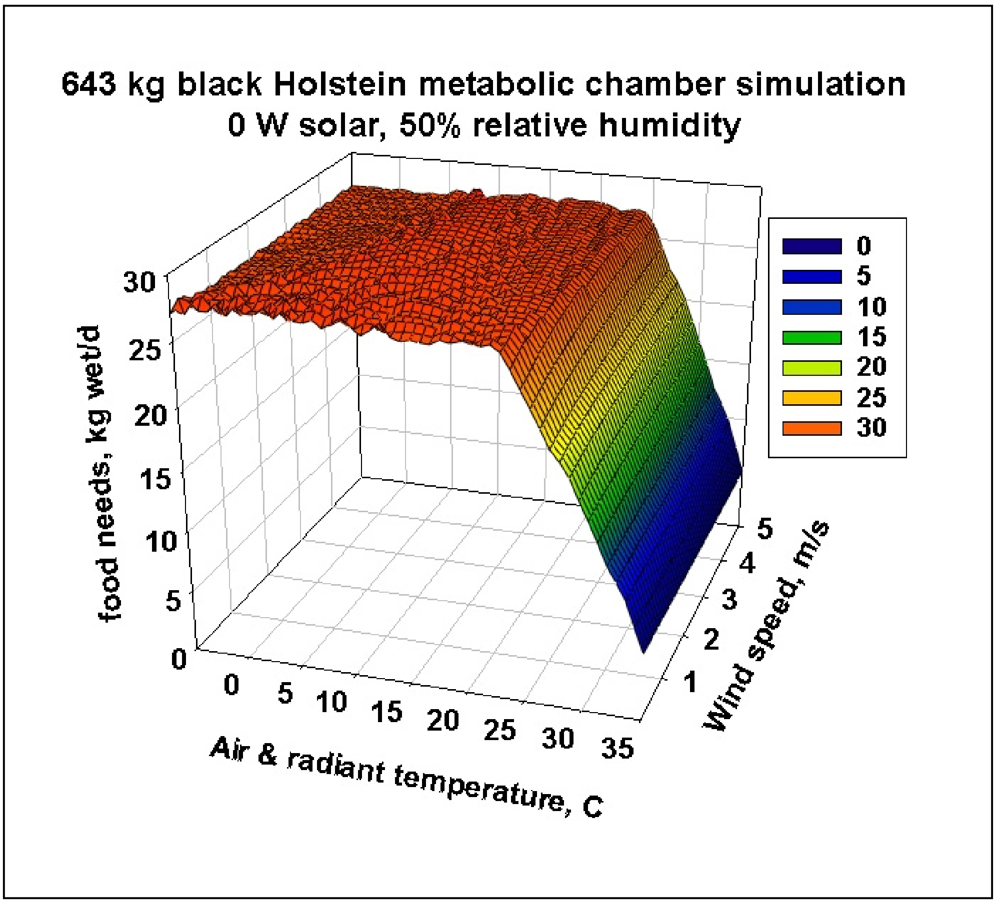



Figure S3. 3D representation of the wet weight food needed to maintain a 50 kg per day milk production target by a 643 kg black Holstein cow. Food consumption is projected to begin to decline at approximately 25 °C. At the lowest windspeeds near 0.1 m/s the transition to reduced feed intake begins at slightly lower temperatures than at higher wind speeds and temperatures as indicated by the horizontal lines on the declining food needs surface.

Figure S4

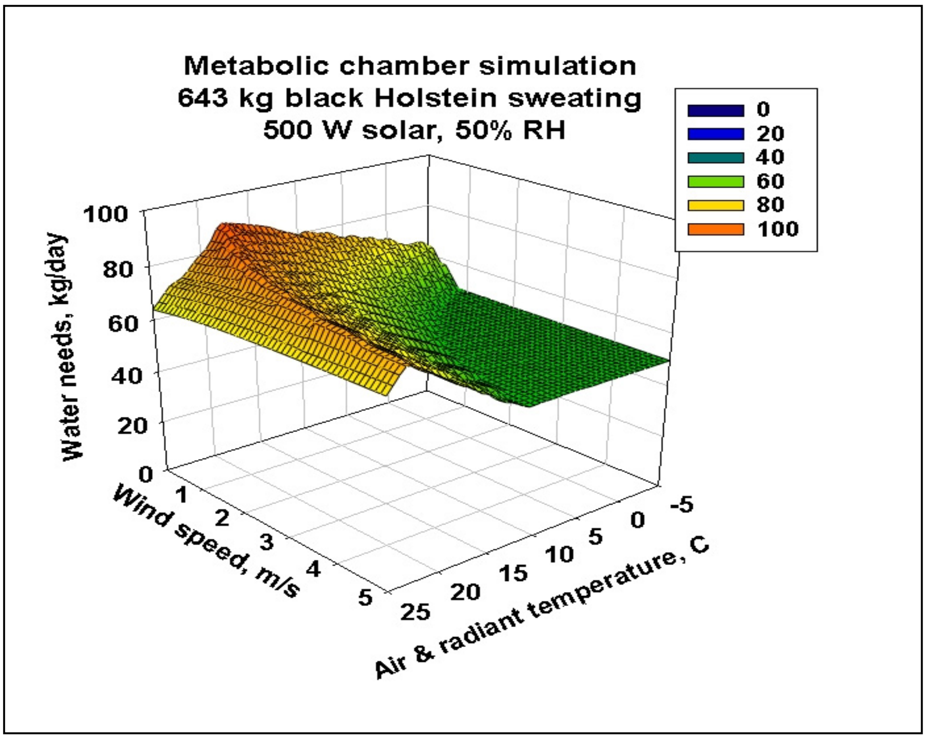
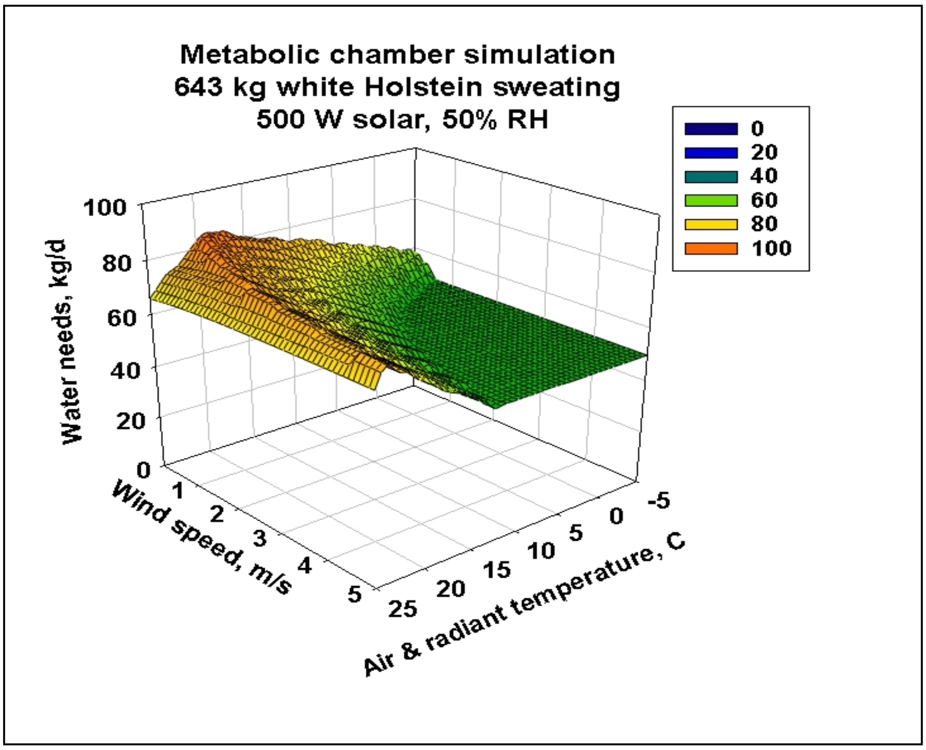



Figure S5




Water needs for a black (top) versus white (bottom) Holstein in the same environment.

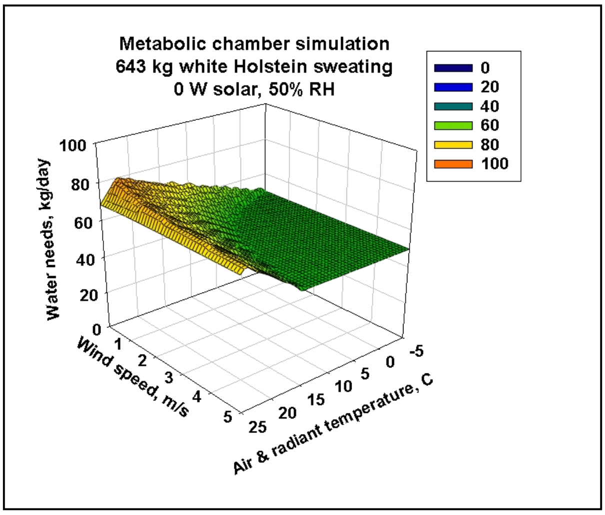



Figure S6a

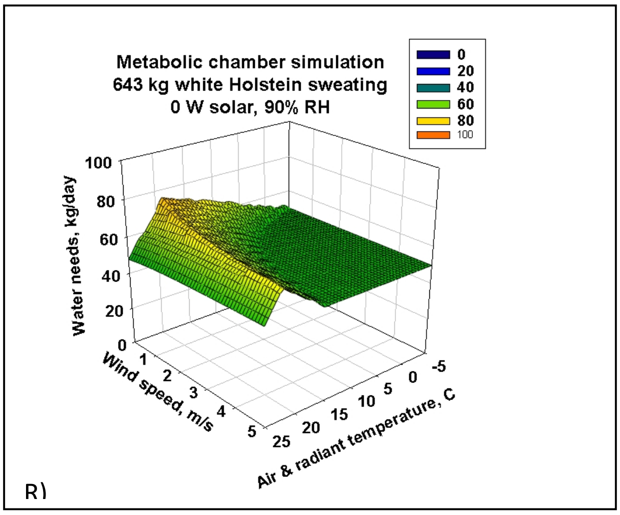



Figure S6b

Water loss for 643 kg, 100% white Holsteins for variation in humidity (L/R columns) and solar radiation (Top/Bottom rows)

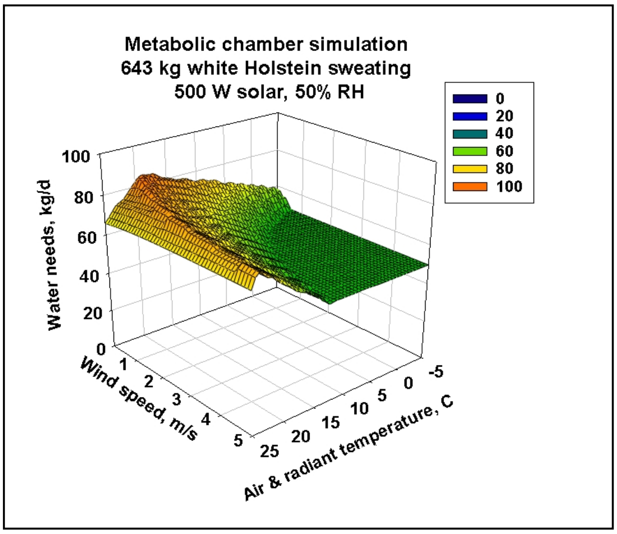



Figure S6c

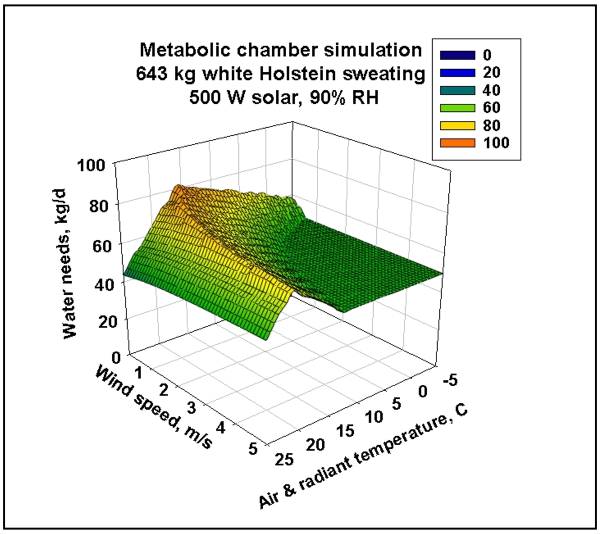



Figure S6d

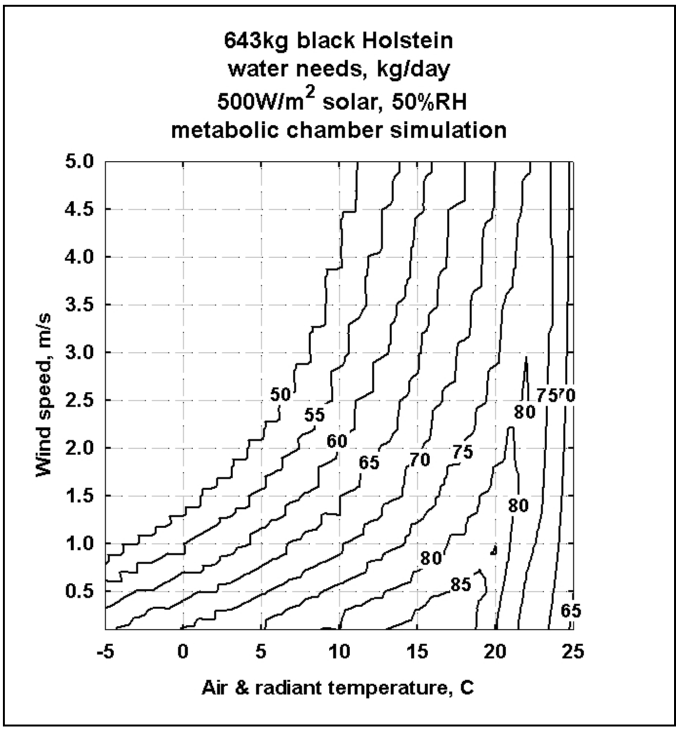



Figure S6e

Contour plots allow for explicit evaluations of responses to multiple variables affecting the response. Figures S6e and S6f demonstrate how haircoat color can modify water requirements as wind and temperatures vary. They also show where climate cliffs occur on the right side of the 'ridge' on these plots where the ridge peak runs from ~17 °C at 0.1 m/s to ~24 °C at 5 m/s. The flat 'plain' of 50 kg/d water loss in the upper left portion of the graph is slightly larger for the white than the black Holstein.

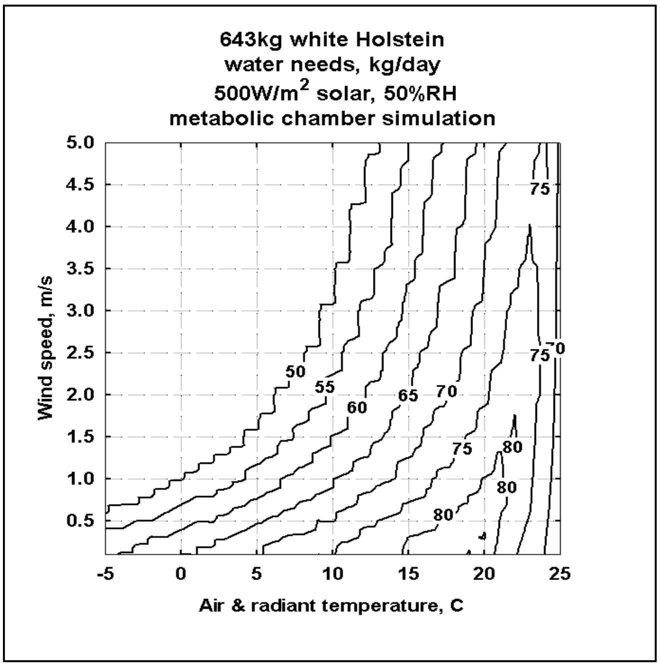



Figure S6f

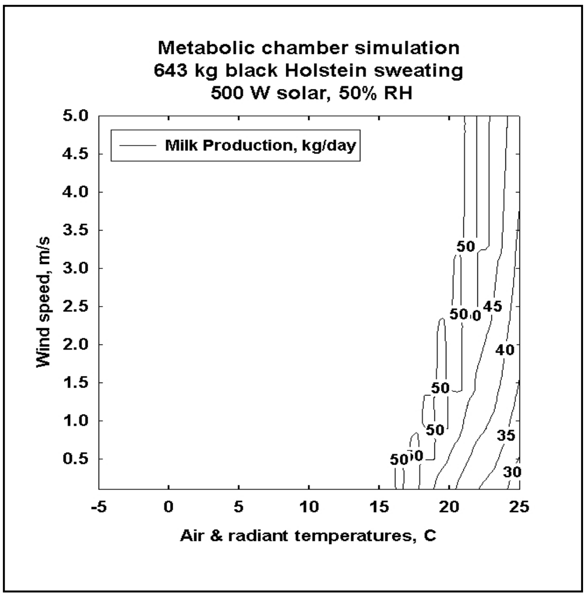



Figure S7a

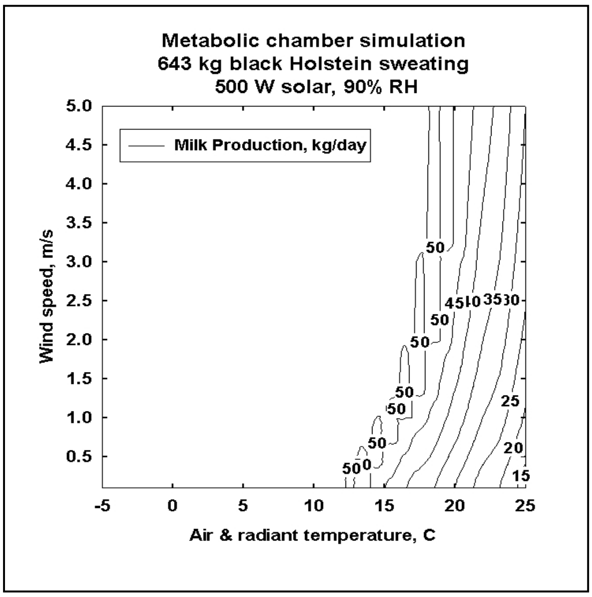



Figure S7b

Effect of relative humidity and coat color on milk production potential of a 643 kg black (top) vs. white Holstein (bottom). The large white area on the left part of the contour plots is the “plain” of where the target 50 kg milk production per day can occur. Contour lines on the right indicate the “cliff” where function is failing.

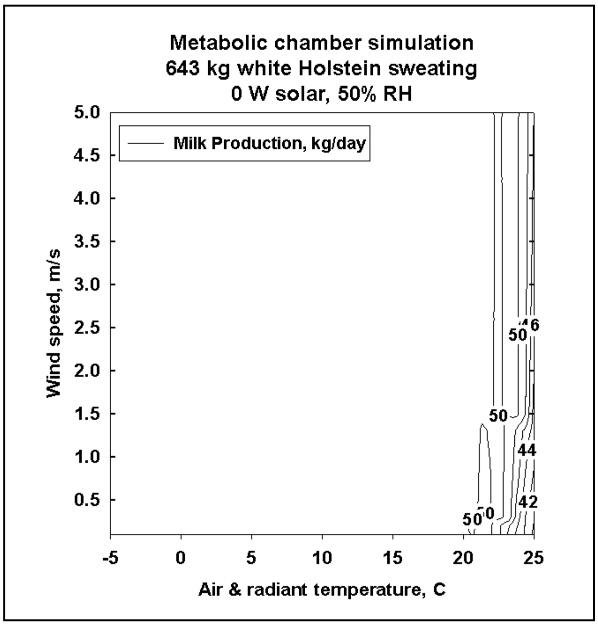



Figure S7c

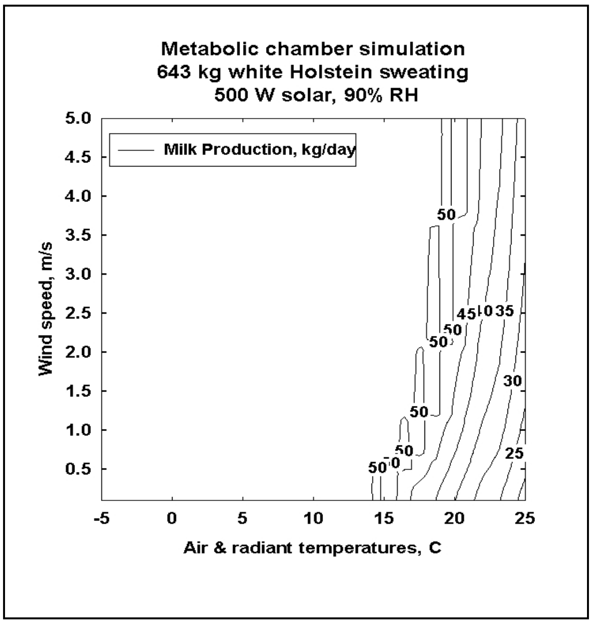



Figure S7d

“THI effects” of solar radiation and wind speed. The addition of solar radiation at 3 m/s moves the edge of the “cliff” back to the left to lower tolerated air temperatures.

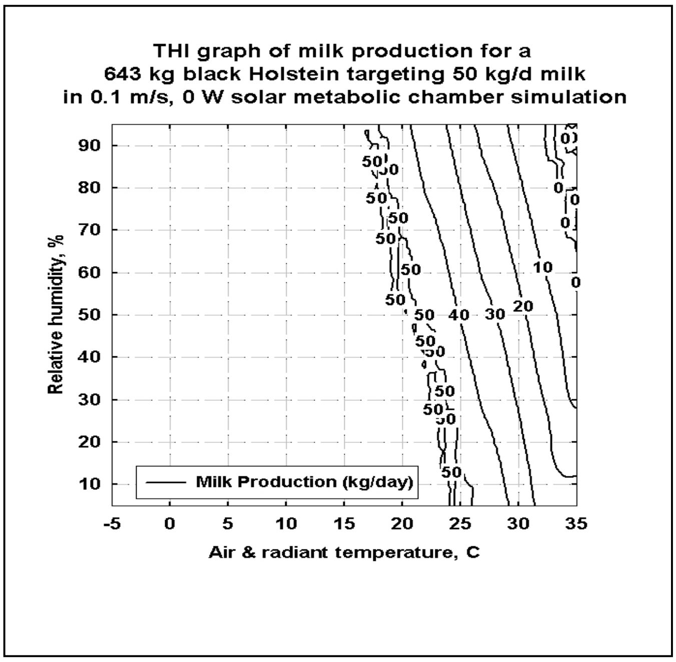



Figure S8a

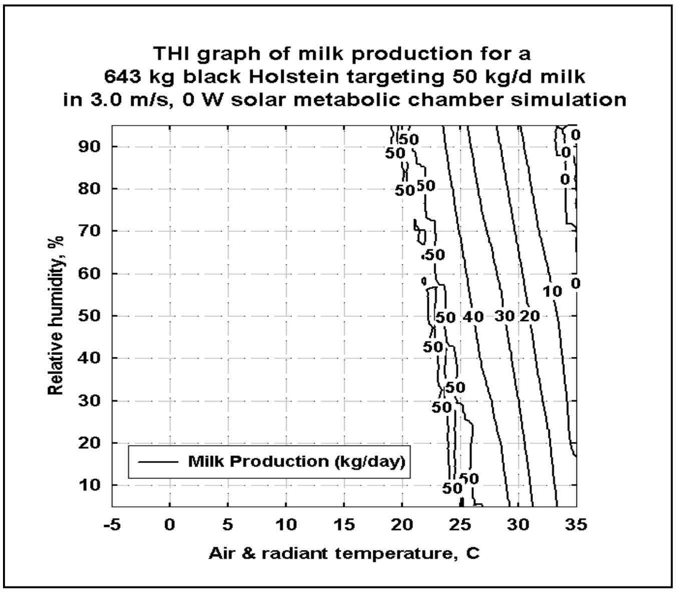



Figure S8b

Figure  S8c looks the same at 2.9 m/s, but at 2.8 m/s, Figure S8d, there is a catastrophic drop in milk production potential that allows for less than 10% relative humidity for any milk production at all.
The reason for the sudden ‘drop’ turns out to be the level of solar radiation, 500 W/m$^2$, in the simulation.

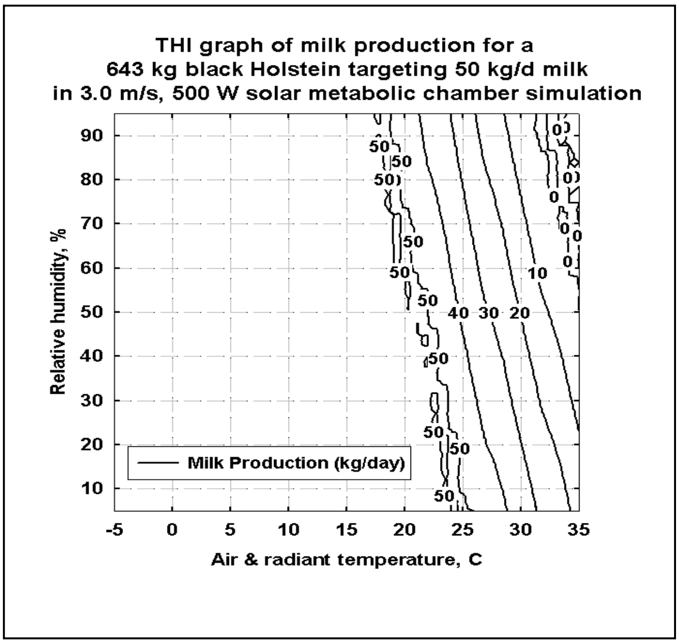



Figure  S8c

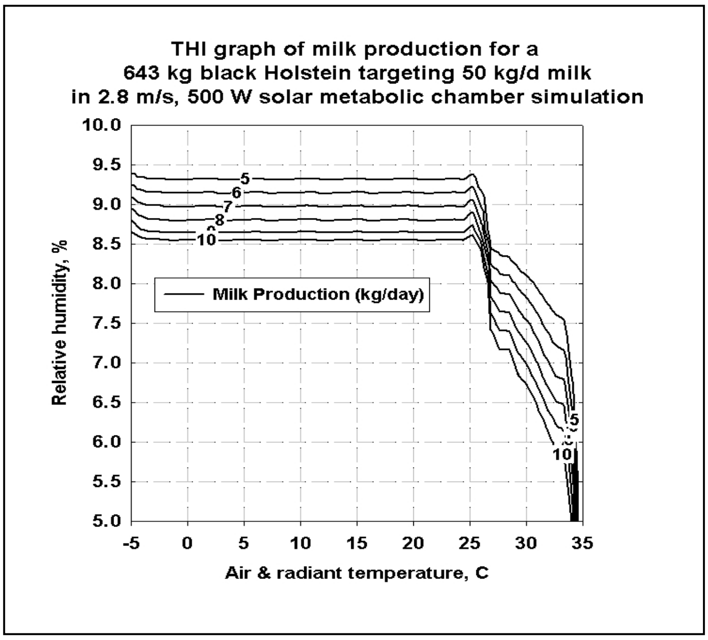



Figure S8d

Figure S8e shows that the 'plain' of milk production is achievable if the solar radiation is decreased to 480 W/m$^2$ at 2.8 m/s wind. Thus a 5$^{th}$ dimension of solar radiation, not typically visible in THI plots, is responsible for this apparent sudden loss of production capacity.

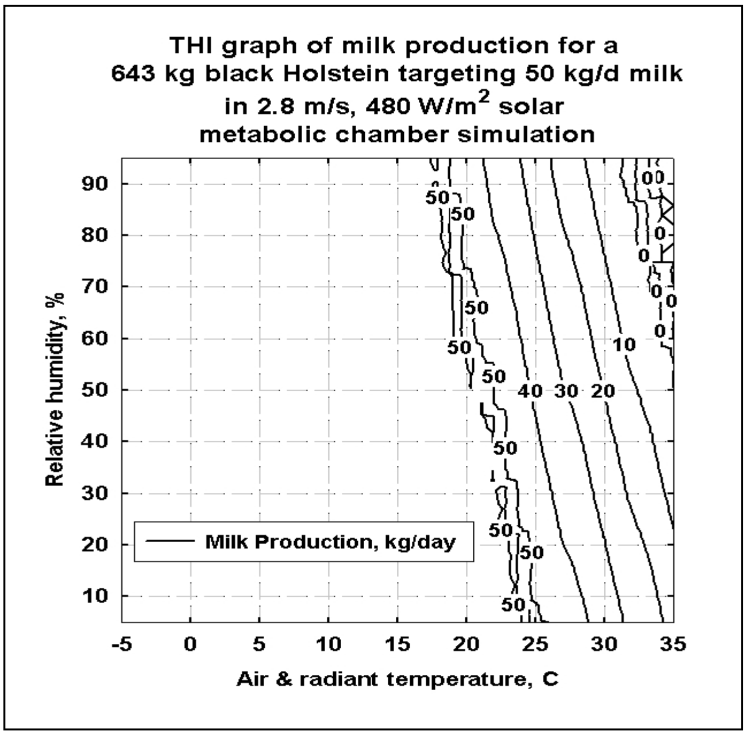



Figure S8e

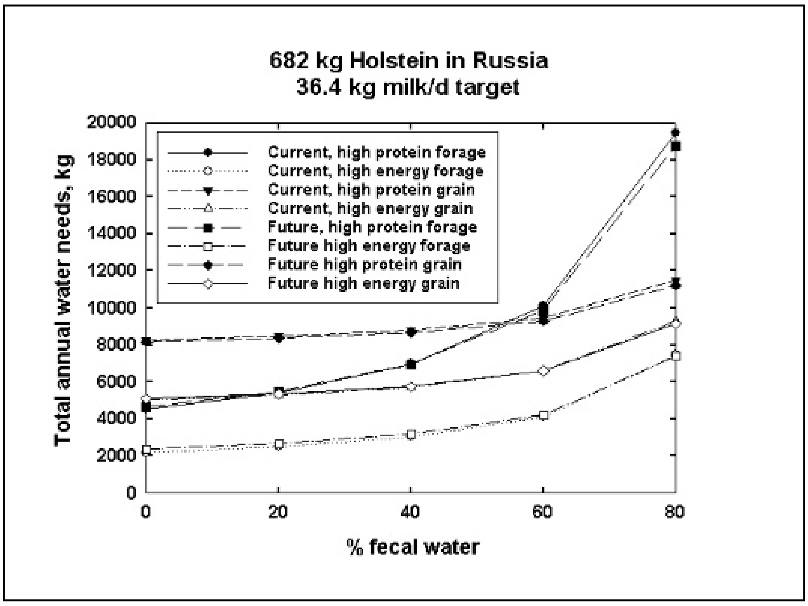



Figure S9a

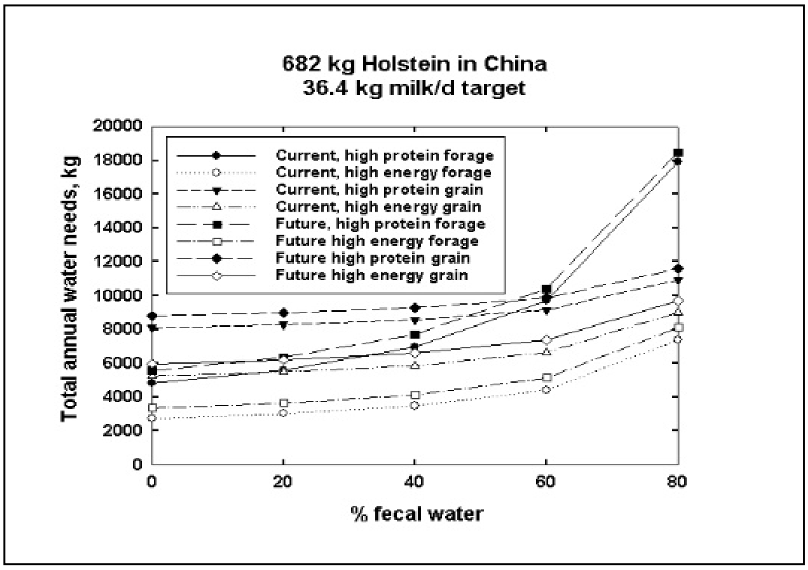



Figure S9b

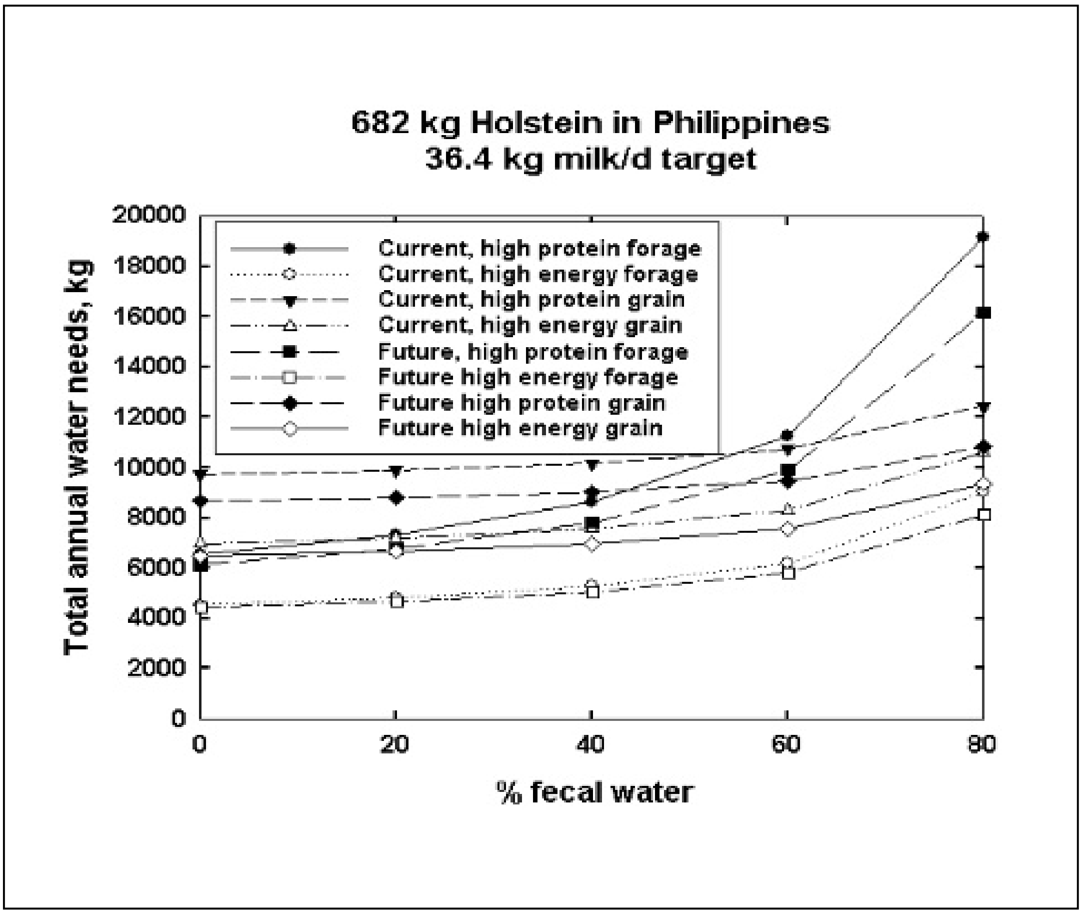



Figure S9c

Figures S9 a-c show the total annual water needs for a 50% black and 50% white free ranging Holstein weighing 682 kg at 60° north latitude (Russia), 30° north latitude (China), and 12° north latitude (Philippines) respectively from top to bottom. The annual water needs are impacted by percent fecal water, diet type and current versus future 3° warmer climates.