Appendix S1

Section S1. Fieldwork and transmitters

With collaborative efforts from California Dept. of Fish and Wildlife (CDFW) and Oregon Dept. of Fish and Wildlife (ODFW), a total of 19 GPS neck collar transmitters (OrniTrack-N44 or OrniTrack-N38, Ornitlea UAB, Vilnius, Lithuania) transmitting using the global system for mobile communication (GSM) were deployed on tule greater white-fronted geese in September 2018 (n= 12; 12–18 September 2018) and 2019 (n= 7; 10–19 September 2019) during 5 rounds of rocket-net trapping on the Summer Lake Wildlife Area in Summer Lake, Oregon. For any given capture either adult male or adult female geese were transmittered to reduce the likelihood of collaring two members of the same family group. Female geese (n=15) generally received a 38mm diameter (38 g) transmitter equipped with two solar panels and male ganders (n=4) received a 44mm diameter (45 g) transmitter equipped with three solar panels. All geese, including non-collared individuals, received a federal aluminum leg band. Capture and marking efforts were permitted under U. S. Geological Survey (USGS) Bird Banding Permit 21142, California Scientific Collection Permit 8090 and the USGS-Western Ecological Research Center Animal Care and Use Committee. GPS relocation data associated with this manuscript are archived with the USGS ScienceBase data repository (Overton et al. 2021). HRRR-Smoke Model output is available from the NOAA-Global Systems Laboratory website (https://rapidrefresh.noaa.gov/hrrr/HRRRsmoke/).

GPS data interval was conditioned on battery level to optimize the tradeoff between transmitter longevity and data quantity. Data collection rates during migration were set at 15 minutes when battery levels were above 75% capacity which reduced to 60 minutes if batteries fell below 75%. The only observed male tule goose migrated in 2019 and had 100% location fix success. Female tule geese migrating in 2019 obtained 94.7% of possible relocations and in 2020 obtained 92.5% of all possible relocations. Fewer than 1% of all relocations were obtained at an interval greater than 30 minutes from the the previous relocation. GPS error was not formally estimated but immobile units assessed prior to deployment had an average error of 31 m and 95% of all errors were less than 62.2 m. Data were transmitted via cellular connection once per day when birds were located in regions with suitable cellular coverage. GPS-derived altitude, was also transmitted with location data. Ground elevation at each location was determined using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation models annotated using the Env-Data system (Dodge et al. 2013). Vertical position derived using GPS is often poorly resolved relative to horizontal position. The rapid data collection interval
enabled us to filter erroneous vertical position (elevations) identified via biologically untenable rates of ascent or descent (>0.5 m sec\(^{-1}\)) from analyses involving vertical distribution of birds relative to smoke density. In addition, locations with estimated elevations greater than 50 meters below ground elevation were also removed while locations less than 50 meters below ground were adjusted to ground elevations. We made no adjustments of points above ground because vertical position error could not be distinguished from flight. In 2019, 3.6% of locations and 4.4% of locations in 2020 were filtered from analyses involving vertical position due to inaccuracy.

**Section S2. Flight duration, distance, and path**

Temporal metrics related to migration were resolved at a resolution less than or equal to 1 hour (maximum relocation interval). One individual provided location data during both 2019 and 2020 fall migrations. Four individuals provided data during fall migration in 2019 only and three different individuals in fall of 2020 only. Start of migration was determined as the first location of a continuous flight path that extended southward or eastward into the Gulf of Alaska. End of migration was determined as the first location occurring within 25 km of Summer Lake Wildlife Area. Duration of migration over the ocean was calculated as the time between the first location occurring over the Gulf of Alaska to the first location occurring over Washington and included resting periods on the water but excluded terrestrial rest stops along the Pacific Coast of Alaska or British Columbia. Time required to transit the La Perouse Bank from approximately 49 degrees latitude to landfall in Washington was also calculated. Migration distance was estimated along a generalized path that excluded recursive movements and drifting due to ocean currents while stopped.

Fall migration started less than one day apart between 2019 and 2020, but the total duration of migration was substantially extended in 2020. The first individual to encounter smoke plumes experienced the shortest delay in completing migration but also travelled the greatest distance to reach Summer Lake Wildlife Area. The direction travelled, relative to Summer Lake, was similar between years north of 49 degrees latitude. However, upon encountering smoke near 49-degrees latitude, migration paths became more disordered with substantial distances flown tangential to the ultimate stopover site (Figure S1).

**Section S3. Energetic deficit**

We calculated a conservative estimate of energetic costs resulting from wildfire and smoke which includes only the increased migration distance birds flew to circumvent fire and smoke and the migration delay experienced on the open ocean where foraging opportunities were assumed to be negligible. Increased disturbance and reduced roosting behavior when occupying previously unused habitats as temporary stopovers was observed, but energy demand resulting from these behaviors was not quantified. For example, some habitats used in western Idaho include small riparian creeks dominated by sagebrush. In addition, the forage supply and foraging behavior undertaken at novel stopover areas was not quantifiable. Therefore, our
assessment of energy deficit assumes birds were able to obtain resources of equal quality and using a similar amount of effort in novel stopover areas as traditional ones which may underestimate energetic recovery needs.

Increased energy demand resulting from migration disturbance was determined from the average extra distance flown in 2020 relative to 2019 and the duration of at-sea stopovers where foraging activities were presumed to be negligible. We used existing energy expenditure estimates of 0.75 kcal km\(^{-1}\) of flight (Aagaard et al. 2018) resulting in an extra 568 kcals (2,376 kJ) expended during migration. Geese spent 1.76 extra days floating off the coast of Vancouver Island and Washington before the smoke plume shifted and they continued migration. We conservatively assume that the only increased energy costs to this delay was thermally neutral metabolism equaling 217 kcal day\(^{-1}\) delayed (Miller and Eadie 2006, Aagaard et al. 2018). These effects resulted in a net energy deficiencies of 950 kcal (3,977 kJ) equivalent to nearly 4.4 days of thermally neutral metabolic rate (Aagaard et al. 2018) or 2.27 days of total energy expenditure in the winter (Mooij 1992) requiring 27.6-41.9 hours of foraging to offset (Nolet et al. 2016). If post-migrating tule geese in the fall exhibited hyperphagic behavior typical of Canada geese (Branta canadensis) during pre-breeding migration periods, when foraging behavior can last five times longer than normal (McLandress and Raveling 1981), these energetic deficits would take 3.7 to 5.6 days before individuals replenished the caloric deficit.

**Section S4. Smoke extent and impact threshold**

Three-dimensional smoke fields from the National Oceanic and Atmospheric Administration’s High-Resolution Rapid Refresh with Smoke model (HRRR-Smoke) are compared with bird tracks to investigate potential impacts of smoke upon migration patterns. The HRRR-smoke system (Ahmadov et al. 2017) is an experimental extension of the meteorological HRRR forecasting system (Ahmadov et al. 2017), a numerical weather prediction model with 3 km horizontal grid spacing running hourly over the continental United States. HRRR-Smoke uses satellite-detected fire radiative power data over the previous 24 hours to determine the location and intensity of wildfires; the injection height for the smoke tracer (PM2.5, mm m\(^{-3}\)) is based on a simple plume rise parameterization (Benjamin et al. 2016). The smoke is then advected by the model accounting for vertical mixing, dry and wet deposition and the 3D smoke state is cycled from one hour’s forecast to the next. The HRRR features sub-hourly radar data assimilation, an advanced hybrid ensemble-variational data assimilation system (Benjamin et al. 2016), and tailored physics parameterizations (Olson et al. 2019). In this study, we used 0 hour forecast output valid every 6 hours (at 05, 11, 17, and 23 UTC) to estimate the temporal evolution of the 3D distribution of smoke.

Elevational gradients of smoke concentrations were linearly interpolated along the z-axis at each goose relocation, allowing predictions specific to each GPS location and interpretation of individual path choice relative to vertical distribution of smoke density. Each goose responded
with at least one departure from typical migration patterns upon encountering wildfire smoke plumes (“impact points”). Impact points occurred when individuals:

1) demonstrated course correction >120 degrees and for longer than 25 km;
2) abruptly dropped altitude to ground level and remained for longer than 12 hours; or,
3) after 14.4 hours of continuous rafting within the ocean (twice the average transit time from Vancouver Island to Washington State in 2019).

Three individuals exhibited single impact points and one indicated two impact points separated by 3 days. Smoke impact thresholds were calculated as the average smoke concentrations throughout observed migration flight altitudes (ground level to 4,000 m) the hour prior to and including impact points (161 µg m⁻³, range: 123-224). The maximum potential region impacted by wildfire smoke was calculated using an isoline that encompassed maximum smoke densities greater than average impact thresholds (161 µg m⁻³).

Literature Cited

Aagaard, K. J., W. E. Thogmartin, and E. V. Lonsdorf. 2018. Temperature-influenced energetics model for migrating waterfowl. Ecological Modeling 378: 46–58.

Ahmadov, R., G. Grell, E. James, I. Csiszar, M. Tsidulko, B. Pierce, S. McKeen, S. Benjamin, C. Alexander, G. Pereira, and S. Freitas. 2017. Using VIIRS fire radiative power data to simulate biomass burning emissions, plume rise and smoke transport in a real-time air quality modeling system in 2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2806–2808.

Benjamin, S., S. Weygandt, J. Brown, M. Hu, C. Alexander, T. Smirnova, J. Olson, E. James, D. Dowell, G. Grell, and H. Lin. 2016. A North American hourly assimilation and model forecast cycle: The Rapid Refresh. Monthly Weather Review 144: 1669–1694.

Dodge, S., G. Bohrer, R. Weinzierl, S. Davidson, R. Kays, D. Douglas, S. Cruz, J. Han, D. Brandes, and M. Wikelski. 2013. The Environmental-Data Automated Track Annotation (EnvDATA) system: linking animal tracks with environmental data. Movement Ecology 1: 3.

McLandress, M. R., and G. G. Raveling. 1981. Hyperphagia and Social Behavior of Canada Geese Prior to Spring Migration. Wilson Bulletin 93: 310–324.

Miller, M., and J. M. Eadie. 2006. The allometric relationship between resting metabolic rate and body mass in wild waterfowl (Anatidae) and an application to estimation of winter habitat requirements. Condor 108: 166–177.

Mooij, J. H. 1992. Behaviour and energy budget of wintering geese in the Lower Rhine area of North Rhine-Westphalia, Germany. Wildfowl 43: 121–138.
Nolet, B. A., A. Kölzsch, M. Elderenbosch, and A. J. van Noordwijk. 2016. Scaring waterfowl as a management tool: how much more do geese forage after disturbance? *Journal of Applied Ecology* **53**: 1413–1421.

Olson, J. B., J. S. Kenyon, W. Angevine, J. M. Brown, M. Pagowski, and K. Sušelj. 2019. A description of the MYNN-EDMF scheme and the coupling to other components in WRF-ARW. NOAA Technical Memorandum OAR GSD–61.

Overton, C. T., A. A. Lorenz, and M. L. Casazza. 2021. Tule Greater White-fronted Goose migration tracks (2019-2022) and atmospheric smoke concentrations (2020). U.S. Geological Survey data release, https://doi.org/10.5066/P9IE7YCH

Yparraguirre, D. R., T. A. Sanders, M. L. Weaver, and D. A., Skalos. 2020. Abundance of Tule Geese Anser albifrons elgasi in the Pacific Flyway 2003–2019. *Wildfowl* **70**: 30–56.
Figure S1: Migration heading relative to destination stopover site.

Movement direction (degrees) relative to Summer Lake Wildlife Area, Oregon, USA during fall migrations in September 2019 (blue) unaffected by wildfire smoke and heavily impact migrations in 2020 (orange). The northern half of fall migration (>49° latitude) showed similar migration trajectories between 2019 and 2020. In 2020, upon reaching wildfire smoke plumes, which occurred within the southern half of migration (<49° latitude), flight paths (direction) became disorganized resulting in long recursive and tangential movements.