Air-quality implications of widespread adoption of cool roofs on ozone and particulate matter in southern California

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Significance

The South Coast Air Basin of California, a region of 16.8 million people, is among the most polluted air basins in the United States. A multidecadal effort to attain federal air-quality standards has led to significant progress, but much more work remains. Are recently implemented statewide building efficiency standards on rooftops counterproductive to these goals? With comprehensive regional models and intensive development of model input parameters, our research has identified the air-quality consequences that are expected to result from these efficiency standards. The results can

inform policies to mitigate some air-quality penalties, while preserving the benefits of building efficiency standards. This work also sheds light on potential future policies aimed at reducing urban heating from pavement surfaces.

Abstract

The installation of roofing materials with increased solar reflectance (i.e., “cool roofs”) can mitigate the urban heat island effect and reduce energy use. In addition, meteorological changes, along with the possibility of enhanced UV reflection from these surfaces, can have complex impacts on ozone and $PM_{2.5}$ concentrations. We aim to evaluate the air-quality impacts of widespread cool-roof installations prescribed by California’s Title 24 building energy efficiency standards within the heavily populated and polluted South Coast Air Basin (SoCAB). Development of a comprehensive rooftop area database and evaluation of spectral reflectance measurements of roofing materials allows us to project potential future changes in solar and UV reflectance for simulations using the Weather Research Forecast and Community Multiscale Air Quality (CMAQ) models. 2012 meteorological simulations indicate a decrease in daily maximum temperatures, daily maximum boundary layer heights, and ventilation coefficients throughout the SoCAB upon widespread installation of cool roofs. CMAQ simulations show significant increases in $PM_{2.5}$ concentrations and policy-relevant design values. Changes in 8-h ozone concentrations depend on the potential change in UV reflectance, ranging from a decrease in population-weighted concentrations when UV reflectance remains unchanged to an increase when changes in UV reflectance are at an upper bound. However, 8-h policy-relevant ozone design values increase in all cases. Although the other benefits of cool roofs could outweigh small air-quality penalties, UV reflectance standards for cool roofing materials could mitigate these negative consequences. Results of this study motivate the careful consideration of future rooftop and pavement solar reflectance modification policies.

urban air quality albedo California Title 24 Los Angeles urban surface modification

The South Coast Air Basin (SoCAB) is a region of southern California encompassing Orange County and the urban portions of Los Angeles, San Bernardino, and Riverside counties. With 16.8 million people, the SoCAB is the second most populous urban area in the United States. A fossil-fuel-dependent transit and goods movement infrastructure along with a well-developed industrial presence within the 27,824-km^2 SoCAB generates significant emissions of oxides of nitrogen (NOx), volatile organic compounds (VOCs), directly emitted primary particulate matter (PM), and secondary PM precursors. Persistent high-pressure systems, ample photochemistry, infrequent rainfall, and ventilation-inhibiting topography also contribute to severe air-quality problems. The SoCAB currently does not attain federal air-quality standards for 8-h O_3, 1-h O_3, annual-averaged $PM_{2.5}$, and 24-h $PM_{2.5}$. Ozone levels within the SoCAB are often the highest in the nation (**1**).

The hot and sunny conditions typically experienced within the SoCAB make urban surface modification a useful strategy to reduce urban temperatures. Meteorological impacts of roofing materials with enhanced solar reflectance (SR, synonymous with “albedo”), colloquially referred to as “cool roofs,” are well-studied and indicate several benefits in urban areas. The replacement of darker materials with high-reflectance surfaces within cities can help mitigate the urban heat island effect (**2**⇓⇓⇓⇓⇓⇓⇓⇓⇓⇓⇓⇓⇓–**14**). Moreover, meteorological modeling suggests that the deployment of cool roofs will reduce afternoon summertime temperatures, leading to reduced cooling energy demands, resulting in a curtailment of greenhouse gas emissions (**15**, **16**) in most urban areas. Cool roofs will also lower the Earth’s radiative forcing by increasing the global albedo (**17**⇓–**19**), although impacts on global climate remain unsettled in the literature (**20**), with recent research suggesting effects are negligible (**4**).

Cool roofs can affect air quality through several mechanisms, although there are far fewer studies investigating these effects compared with the wealth of meteorological and climatological studies. Because the air-quality effects of urban surface modification by cool roofs are complex and nonlinear, comprehensive emissions processing, meteorological, and chemical transport models are needed to accurately determine potential impacts on air quality for policy-making purposes. Potential changes in mixing height and ventilation (**21**) will affect ambient pollutant concentrations. Cool roofs can reduce temperature-dependent emissions of precursors to O_3 and PM in urban areas by lowering ambient temperatures, resulting in a slower rate of VOC evaporation and NOx emissions (**14**). In addition, the atmospheric reactions that produce O_3 are slower at lower temperatures. A handful of studies modeled the effect of cool-roof installations on O_3 concentrations during short-term multiday O_3 episodes in the SoCAB (**22**⇓⇓⇓–**26**). Population-weighted O_3 exposures were reduced with an increase in urban SR; however, O_3 concentrations in the less-populated eastern SoCAB exhibited O_3 increases. Further increases in surface SR led to smaller net reductions in O_3 because significant weakening of the sea breeze led to reduced vertical mixing.

To the authors’ knowledge, all but one (**29**) of the previous studies investigating the role of cool-roof materials on air quality assume that widespread adoption of cool roofs will not change UV reflectance (UVR) (**2**, **22**⇓⇓⇓⇓–**27**). Increases in UVR can significantly affect photochemical production of O_3. For example, O_3 concentrations in the Uintah Basin are elevated in the winter during periods of snow cover due to increased UV reflectivity and limited mixing from reduced surface heating (**28**). Fallmann et al. (**29**) modified building SR for all urban grid cells in Stuttgard, Germany from 0.2 to 0.7 across all wavelengths. Although this increase in UVR is unrealistically high, the authors saw a significant increase in peak O_3 concentrations during a clear-sky, sunny period, which they attribute to increases in reflected UV radiation.

In this research effort we aim to rigorously evaluate the air-quality effects in the SoCAB of current cool-roof installation policies in California Title 24 Building Energy Efficiency Standards (Title24) (**30**). Besides O_3, we also focus on $PM_{2.5}$ concentrations, a pollutant that largely drives the health impacts of air pollution in southern California (**31**) and whose link to cool-roo[illegible]n [illegible]ith

newly analyzed data on the UVR of hundreds of real-world roofing products, we directly evaluate the assumption used in previous studies that standard and cool roofs have nearly the same UVR and then probe the sensitivity of UVR on resulting pollutant concentrations. Rather than focusing on specific air-pollution episodes, we have conducted a collection of comprehensive simulations over an entire calendar year. We developed a high-resolution database of building rooftop areas classified by land-use category to project future SR after full implementation of Title24 standards in the SoCAB. WRF v3.6, a state-of-the-science meteorological model, was used to forecast changes in meteorology induced by cool roofs. The temperature-dependent 2012 SoCAB emissions inventory (**1**) and a modified version of the state-of-the-science Community Multiscale Air Quality Model (CMAQ version 5.0.2) were then used to project future O_3 and $PM_{2.5}$ concentrations after cool-roof implementation.

Materials and Methods

Projecting Future SR.

Determining the effects of Title24 standards on SR requires information on the current SR and the total rooftop area in each Title24 building category. Title24 standards prescribe that new or renovated rooftops meet SR standards that are based on climate zone (SI Appendix, Fig. S1) and building type (**30**) (**Table 1**). We determined the rooftop area of each Title24 building category in every model grid cell with land-use data for 2012 from the Southern California Association of Governments (SCAG) and building footprint data from the US Army Corps of Engineers (**32**). See SI Appendix.

Table 1.

Current and future SR values corresponding to Title24 categories

We used monthly Moderate Resolution Imaging Spectroradiometer (MODIS) measurements of SR (**33**) to determine base-case values for each 4-km model grid cell. The current SR of rooftops for each Title24 category in the SoCAB was calculated by combining recent aircraft-based remote sensing measurements of rooftops in Los Angeles and Long Beach, CA (**8**, **9**) with SCAG land-use data (**Table 1**). The projected future building SR, set by the Title24 standards, along with the current building SR, calculated with the remote sensing measurement data, allowed us to determine the expected change in SR in the fraction of each grid cell occupied by buildings and determine the monthly SR for each grid cell if all rooftops meet Title24 standards. **Fig. 1**A details the calculated change in grid-cell average SR in response to full implementation of Title24 standards.

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Fig. 1.
(A) Change in SR (Title24 – baseline) used for WRF simulations. (B) Maximum possible change in UVR (Title24 – baseline) used for CMAQ simulations.

Projecting UVR for Chemical Transport Modeling.

Photolysis reactions are wavelength-dependent (**34**); therefore, capturing changes in photochemistry from Title24 requires careful consideration of wavelength-dependent reflectances. In situ remote sensing measurements of rooftop UVR are not available. However, several studies measured the wavelength-dependent spectral reflectance of roofing materials (**8**, **9**, **35**⇓–**37**). To bound the possible change in wavelength-dependent reflectance, **Fig. 2** presents spectral reflectance measurements (**8**, **9**) for a wide variety of traditional and cool roof materials as a function of wavelength for high slope (**Fig. 2**A) and low slope (**Fig. 2**B) roofing materials (SI Appendix, Table S2). We define cool roofs, based on Title24 standards, as those with an SR above 0.20 and 0.63 for low-slope and high-slope roofing materials, respectively. To serve as an extreme upper-bound increase in UVR, we set the maximum change in reflectance at each CMAQ wavelength range to be the largest difference between the cool and standard roofing materials (**Fig. 1**B) and applied these dif ac egories based on their corresponding area in each grid cell. Projection sc

comprehensively in the SI Appendix. We also explored the scenario where UVR does not change to serve as a lower bound. Each of these scenarios was used to drive photochemistry in the Title24 simulations in CMAQ. The Title24 SR changes as derived in the previous paragraph were used for the 410- to 850-nm wavelength band in the CMAQ simulations.

Fig. 2.
Range of wavelength-dependent reflectance of cool and standard roofing materials for high-slope (A) and low-slope (B) applications.

Emissions Processing.

On-road NOx and VOC along with biogenic VOC emissions profiles are dependent on meteorology. Annual hourly emissions profiles were developed as a function of the baseline and Title24 meteorological fields for the 2012 base year. The SoCAB emissions inventory is presented in ref. **1** and details of the emissions processing are presented in ref. **38**. Changes in NOx and VOC emissions in the baseline and Title24 simulations are small, mainly due to the similarity in the meteorological fields. Within the SoCAB, on average during the O_3 season, VOC em[illegible] d[illegible] tons per day) and NOx emissions are reduced by 8×10^{-4}% (0.004 [illegible]) i[illegible]rio.

Within the SoCAB, changes in power-generation emissions are expected to be insignificant with the widespread implementation of cool roofs and are not accounted for in the modeling. Emissions from power generation are only responsible for 0.4% of the total NOx emissions in the 2012 emission inventory. Additionally, only 37% of the total electricity consumed is generated within the SoCAB (**1**).

Meteorological and Chemical Transport Modeling.

WRF version 3.6.1 was used with a North American Regional Reanalysis field to simulate 2012 meteorology on three nested grids, with an inner 4-km grid covering the modeling domain (SI Appendix, Fig. S9). (Details of the model setup are available in ref. **38**.) WRF model performance is summarized in SI Appendix, Figs. S10–S19. Two year-long simulations were performed: a base case using the MODIS-derived SR fields and a Title24 case using the modified SR fields detailed above assuming that all buildings in the SoCAB meet Title24 rooftop SR requirements.

CMAQ version 5.0.2 was used to simulate air quality without dynamic coupling within a 624- × 408-km modeling domain on a 4-km grid with 18 vertical layers. Extensive details of the modeling protocol are presented in ref. **38**. Modification of the CMAQ code allowed us to calculate spatially resolved photolysis rate constants based on wavelength-dependent reflectance fields. As with any modeling study, results are dependent on the model accurately capturing the physical and chemical processes under investigation. SI Appendix, Figs. S20–S28 summarize the ability of CMAQ to predict measured concentrations of O_3 and $PM_{2.5}$ throughout the SoCAB.

Changes in annual averaged $PM_{2.5}$, daily maximum 8-h O_3, and daily maximum 1-h O_3 concentrations were evaluated across the modeling domain. Student's t tests for paired samples were conducted to determine whether changes in concentration across different scenarios were statistically significant. Differences with P values less than 0.05 were assumed to be statistically significant.

To evaluate the impact of widespread cool-roof installation toward attainment of federal ambient air-quality standards, relative response factor projections were also conducted to calculate changes in design values (DV). This strategy uses the ratio of Title24 vs. baseline concentrations to adjust measured values, cancelling out many of the systematic uncertainties responsible for concentration biases. This analysis is consistent with Environmental Protection Agency (EPA) modeling guidance (**39**) and is presented in ref. **38** with a summary in SI Appendix. Data and scripts, with minor exclusions (SI Appendix), are available with a South Coast Air Quality Management District public records request.

Results and Discussion

Changes in Meteorology.

WRF simulations of 2012 meteorology representing the baseline (MODIS-derived SR) and Title24 (SR modified for cool-roof adoption) cases are summarized in **Fig.** [illegible] temperatures are projected to decrease throughout the SoCA[illegible]th[illegible]ses

(~0.35 K) in areas with the largest change in SR. Changes in the daily maximum planetary boundary layer height (PBLH) (**Fig. 3**B) are negative; the mixed layer height will decrease by 40–65 m in the most polluted areas of the SoCAB in the Title24 scenario, a significant difference compared with model-predicted average daily maximum mixed layer heights of 1–2 km. A decrease in surface temperature can reduce the buoyancy of the surface air, leading to a reduction in vertical mixing. Lower surface temperatures on land decrease the land–sea temperature gradient, slowing down the daytime sea breeze—an important mechanism that drives relatively clean marine air into the SoCAB. The average of the 9 AM-to-3 AM ventilation coefficient (VC), the integral of the horizontal wind velocity with respect to height at all layers below the maximum mixing depth (**40**) (**Fig. 3**C), decreases throughout the SoCAB with implementation of Title24. Daily profiles of the change in several meteorological variables are presented in SI Appendix, Figs. S29–S32.

Fig. 3.
(A) Change in annual average daily max temperatures (Title24 – baseline). (B) Change in annual average daily maximum PBLH. (C) Change in annual average VC calculated between 9 AM and 3 PM. Gray hashed cells indicate that differences are not statistically significant ($P > 0.05$).

Changes in $PM_{2.5}$ Concentrations.

Several year-long CMAQ simulations were conducted to determine the individual effects of changes in meteorology, emissions, enhanced SR, and a range of hypothetical changes in UVR. **Fig. 4**A shows the change in annual $PM_{2.5}$ concentrations between the baseline simulation (scenario I in **Table 2**) and a simulation using Title24 meteorology, emissions resulting from the Title24 meteorology, and the assumption that UVR does not increase (scenario IV). Average $PM_{2.5}$ concentrations increase throughout the SoCAB, presumably caused by reductions in mixing heights and VCs, as well as partitioning of semivolatile species to the particle phase at lower temperatures. In the populated central Los Angeles region and Long Beach, annual $PM_{2.5}$ concentrations are projected to increase by approximately 0.3 $\mu g \cdot m^{-3}$. **Fig. 4**B illustrates the change in the number of days that exceed the 24-h $PM_{2.5}$ standard of 35 $\mu g \cdot m^{-3}$ (scenario IV – scenario I). These changes are location-dependent, with increases in Los Angeles and the Inland Empire where $PM_{2.5}$ is typically highest.

Fig. 4.

(A) Change in annual average $PM_{2.5}$ concentrations (scenario IV – scenario 1). The green circle indicates the location of the highest annual $PM_{2.5}$ measured DVs in the basin. Seasonal differences in PM [illegible] in SI Appendix, Fig. S24. (B) Change in the number of 24-h $PM_{2.5}$ federal standard (35 $\mu g \cdot m^{-3}$) exceedanc [illegible] (sc [illegible] Gray hashed cells indicate that differences are not statistically significant ($P > 0.05$ [illegible] [illegible]age.

Table 2.
Simulated changes in $PM_{2.5}$ and O_3 at polluted locations

Changes in annual averaged $PM_{2.5}$ at the Mira Loma monitoring location—the most polluted $PM_{2.5}$ station in the SoCAB—for each simulation are presented in **Table 2**. Implementation of Title24 emissions (scenario III) does not affect $PM_{2.5}$ concentrations relative to the baseline scenario (scenario I). However, the inclusion of Title24 meteorology (scenario IV) leads to an annual average $PM_{2.5}$ increase of 0.19 ± 0.007 $\mu g \cdot m^{-3}$. Increases in UVR (scenario V) lead to minimal changes in $PM_{2.5}$ concentrations.

Changes in SoCAB maximum annual and 24-h $PM_{2.5}$ policy-relevant DVs calculated with the EPA-recommended relative response factor approach are also shown in **Table 2**. SoCAB maximum annual DVs are expected to increase by approximately 0.2 $\mu g \cdot m^{-3}$ even if increases in UVR are avoided—important compared with the 12 $\mu g \cdot m^{-3}$ federal standards. Twenty-four-hour $PM_{2.5}$ DVs are projected to increase by 0.62–0.65 $\mu g \cdot m^{-3}$ depending on changes in UVR—important compared with the 24-h $PM_{2.5}$ standard of 35 $\mu g \cdot m^{-3}$.

Changes in Ozone Concentrations.

Fig. 5 shows changes in daily maximum 8-h O_3 ($DM8HO_3$) concentrations averaged over the O_3 season (May 1–September 30) for two scenarios. **Fig. 5**A shows the changes expected if Title24 were fully implemented but UVR was held constant (scenario IV – scenario I). O_3 concentrations largely decrease throughout the SoCAB, with the exception of the Redlands area, which typically experiences the highest O_3 concentrations in the SoCAB. However, most residents in the SoCAB live in areas that will experience a decrease in O_3 under this scenario. Whereas the number of 75 ppb exceedance days is relatively unchanged in the most populated areas of the SoCAB, the number of exceedance days increase in the region surrounding Redlands (SI Appendix, Fig. S35A). **Fig. 5**B shows changes in O_3 concentrations resulting from an upper-bound change in UVR (scenario V – scenario I). Increases in average $DM8HO_3$ concentrations are expected in most of the SoCAB in this scenario (**Fig. 5**B). This translates to large increases in the number of exceedance days throughout the SoCAB (SI Appendix, Fig. S35A).

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Fig. 5.
(A) Change in annual average $DM8HO_3$ values (scenario IV) with the assumption that UVR does not change with widespread installation of cool roofs. The green circle indicates the location of the highest 8-h O_3 measured DVs in the basin. (B) Change in annual average $DM8HO_3$ values with the assumption that UVR increases are consistent with the maximum possible increase based on roofing products currently available (scenario V). Gray hashed cells indicate that differences are not statistically significant ($P > 0.05$). Image represents 3- × 3-cell moving average.

Table 2 details changes in mean +/− standard error (SE) $DM8HO_3$ concentrations at Redlands, the station with the highest 8-h O_3 DV. Changes in 1-h averaged daily maximum O_3 ($DM1HO_3$) concentrations are presented for Fontana, the monitoring station with the highest 1-h DVs in the SoCAB. Ozone concentrations are neither sensitive to increases in visible and IR reflectance (scenario II) within CMAQ nor to decreases in emissions inherent in the Title24 scenario (scenario III). Simulations with Title24 meteorology produce increases in averaged $DM8HO_3$ concentrations (scenarios IV and V). Depending on the magnitude of UVR increases, $DM8HO_3$ concentrations are projected to increase by 0.04 ± 0.013 (scenario IV) to 0.66 ± 0.015 ppb (scenario V), whereas $DM1HO_3$ concentrations are projected to change by −0.040 ± 0.023 to 0.96 ± 0.026 ppb. Although the increase in UVR in the upper-bound case is relatively small, ranging from 0 to 0.027 depend[illegible] is still extremely sensitive to these increases. The projected ch[illegible] or 8-h

and 1-h O_3 are presented in **Table 2**. Changes in O_3 concentrations and DVs are linearly dependent on the degree of UVR increases (SI Appendix, Fig. S33 and Table S1). The SoCAB maximum 8-h DV increases by 0.3 ppb with a constant UVR across the domain to 1.3 ppb with the UVR at the upper bound. Behavior of the 1-h SoCAB maximum DV is more complex. If increases in UVR can be avoided, the 1-h DV is expected to decrease by 0.4 ppb. However, if concentrations are simulated with maximum increases in UVR, 1-h O_3 DV concentrations can increase by 1.9 ppb. This counterintuitive behavior can be explained partially with **Fig. 5**. Fontana is further west than Redlands and is in the region where O_3 concentrations decrease when UVR is held constant and increase when UVR is at its maximum value. This illustrates the competition between the many factors governing O_3 concentrations that can change with cool-roof implementation.

Policy Implications.

Attainment of the 75-ppb 8-h O_3 standard by 2031 in the SoCAB is an extremely challenging air-quality goal, requiring an additional 55% reduction in NOx emissions beyond all existing regulations (**1**). Compliance with Title24 cool-roof standards may make attainment of this goal more difficult, even if future UVR increases are small. Scenario V assumes that buildings adopt cool roofing products with increase in UVR at an extreme upper bound. The actual increases in UVR throughout the SoCAB will depend on the individual roofing products that are chosen for installation. Although more realistic UVR increases cannot be projected without knowledge of the individual cool roofing products that are adopted, our analysis indicates that UVR will likely increase when replacing standard roofs with cool roofs. Whether ozone ultimately increases or decreases in the most populated areas of the basin will depend on the relative importance of multiple physicochemical pathways, including ozone decreases from temperature reductions, ozone increases from reduced ventilation and mixing, and ozone increases from possible UVR increases. Different magnitudes of SR increase or UVR increase may change the dominating mechanisms. We also simulated 2031 DVs with the presence of full Title24 implementation and full implementation of the proposed South Coast Air Quality Management District control strategy (**1**). We estimate that even if UVR increases can be entirely avoided, Title24 could increase the 2031 8-h DV by 0.3 ppb and the 2031 1-h DV by 1.1 ppb. These increases in O_3 concentrations are consequential in light of the cost to reduce precursor emissions to achieve a corresponding reduction in O_3 concentrations.

Implementation of Title24 standards was used as the basis for this analysis; however, several factors may influence future adoption of cool roofs. Municipalities such as Los Angeles and Pasadena have cool-roof ordinances that can lead to increases in SR beyond what would be expected with the Title24 standards. In addition, widespread adoption of solar photovoltaics and Title24 cool-roof installation exemptions for the implementation of equivalent energy savings measures could also affect future changes in urban reflectance.

The O_3 concentration sensitivity to small changes in cool-roof UVR supports the establishment of a standard regulating the UVR of certified cool-roof materials. C ri ific SR standards for consideration as a cool-roof material. Establishr di could

help minimize inadvertent increases in O_3. Furthermore, it is possible that a reduction in UVR below current values will lead to improvements in O_3 air quality throughout the SoCAB; this may be a cost-effective O_3 control strategy. Remote sensing measurements of the current rooftop stock to survey UVR could help set standards such that cool-roof materials do not lead to increases in UVR when they replace existing rooftops.

When assessing the impacts of cool roofs, it is important to consider all environmental and economic consequences. For example, benefits from a reduction in heat-related mortality may outweigh the increase in mortality from enhanced $PM_{2.5}$ pollution. Also, widespread increases in urban SR can help to combat the local impacts of climate change. Potential energy bill savings are also an important benefit. In addition, there are other mechanisms to control ambient air pollution such as emission reductions, whereas tools for mitigation of the urban heat island effect are more limited. Without a comprehensive analysis of all of the benefits of cool roofs it would be a mistake to discourage this technology solely on the basis of air quality alone.

Relatively small changes in surface reflectance lead to significant impacts in O_3 and $PM_{2.5}$. Results of this analysis also shed light on the choice of pavement materials and cool pavements, a potentially more important driver of overall urban SR and UVR. Analysis of impervious surface area (**41**) along with the rooftop area database developed for this paper indicates that there is significantly more pavement area in the SoCAB than rooftop area (1,900 km^2 of pavement area vs. 1,040 km^2 of rooftop area). (SI Appendix, Fig. S36 presents the spatial distribution of pavement area throughout the SoCAB.) In addition, only a fraction of the total rooftop area was modified for projections of air quality because Title24 does not affect rooftops in every climate zone. Therefore, the SR and UVR of pavements may be an important driver of regional air quality and human exposure to UV radiation and should be considered when evaluating cool pavement materials.

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Footnotes

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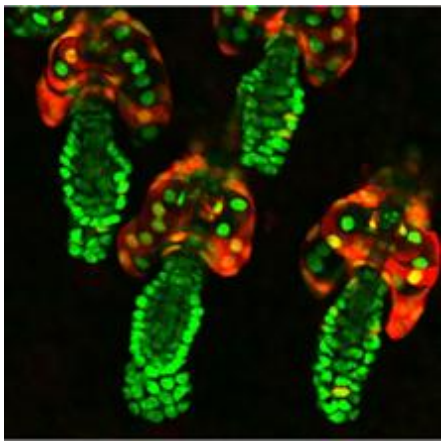

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