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Fires in protected areas reveal unforeseen costs of Colombian peace

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Armed conflict, and its end, can have powerful effects on natural resources, but the influence of war and peace on highly biodiverse tropical forests remains disputed. We found a sixfold increase in fires in protected areas across biodiversity hotspots following guerrilla demobilization in Colombia, and a 52% increase in the probability of per-pixel deforestation within parks for 2018. Peace requires urgent shifts to include real-time forest monitoring, expand programmes to pay for ecosystem services at the frontier, integrate demobilized armed groups as staff of protected areas, and establish a domestic market for frontier deforestation permits.

The signing of Colombia's peace accords late in 2016[1,2] signalled the end of a decades-long struggle between the government and the Fuerzas Armadas Revolucionarias de Colombia (FARC) guerrillas across the country's vast forested frontier. The Colombian accords included language on sustainable development[3], but guerrillas often had forest conservation policies of their own, enforced episodically and at gunpoint[4]. While the practice of conservation may have been incidental to the FARC's political and economic objectives at the forest frontier, armed conflict curbed the transformation of vast forests. Indeed, the transformation of these forest frontiers into deforestation hubs with the end to the conflict was predicted before any empirical data were available[5].

The relationship between armed conflict and forest resources is itself fraught[6,7]. While recent analyses show wildlife declines across Africa in tandem with warfare[8], armed conflict can promote conservation. For example, by effectively limiting the exploitation of natural resources, local conflicts drove the recovery of biodiversity in Central America[9]. With 15 new large-scale civil wars worldwide since 2003 (6 in densely forested countries in Africa and Southeast Asia[10]), there is a growing need to understand the relationship between armed conflict and sustainability. Hence, understanding how the transition from conflict to post-conflict affects forests is crucial to mitigate both carbon emissions and biodiversity loss in Colombia[1], and many biodiversity-rich areas plagued by armed conflict worldwide[8].

Although generally low, deforestation rates in Colombia have been accelerating in the 2000s, particularly after 2007. Forest loss since then has been concentrated along dynamic agricultural frontiers in the global biodiversity hotspots of the northwestern Amazon, remnant Andean forests in the Caribbean, and the Andean forests at the northern end of the Cordillera Oriental[11]. Detailed spatial analyses of the Amazonian deforestation front have revealed that fires in the dry season[12,13] can be used to predict forest loss with greater precision than other alert systems[14].

The causes of variation in fires in the Colombian frontier are multiple and interacting, from climate change and the El Niño Southern Oscillation to edge effects and agricultural expansion[11]. However, shifting environmental conditions should similarly affect entire regions, and not discriminate between protected areas, their buffer zones and unprotected areas. Therefore, by comparing fire frequency in 2017 and 2018 (Supplementary Information) and focusing on differences between protected areas and adjacent areas, we can disentangle environmental and human drivers of fire frequency. A compelling case can then be made for the end of guerrilla warfare as a powerful driver of anthropogenic fires and forest loss. Climate-driven shifts in fires would affect protected areas and other areas in roughly similar proportions, and similar changes would be expected within and outside areas formerly controlled by FARC guerrillas.

Instead, the disproportionate increase in fires within protected areas formerly under FARC control connects deforestation to the transition from armed conflict to post-conflict (Fig. 1). While protected areas have never been immune to forest loss, deforestation primarily proceeds from the inside out, as edges are more vulnerable to frontier dynamics, fire and transformation[15,16]. Therefore, if caused solely by background frontier dynamics, fires and concomitant deforestation in protected areas should concentrate in buffer zones. Furthermore, if changes in fire frequency are unrelated to guerrilla demobilization, areas formerly under FARC influence should show increases no greater than at other sites. However, increases in fire incidence have been concentrated inside protected areas formerly under FARC control, particularly along the Picachos–Tinigua–Macarena axis (Supplementary Fig. 1). While fires have increased from 2017 to 2018 in the 5 km buffer zone around protected areas, a disproportionate, sixfold increase in fires inside nominally protected areas signals the arrival of new dynamics linked to FARC demobilization.

Using a published model of deforestation as a function of fire location[17], the spike of fires in Picachos–Tinigua–Macarena translates into increased deforestation (Supplementary Information). Importantly, and independent of model predictions, the 2018 Landsat data indicate a jump in deforestation within the protected areas from 78 km^2 (estimated by Hansen et al.[18] for 2017) to 132 km^2 (a 69% increase) for 2018. Based on changes in fire frequency only, the probability of per-pixel deforestation within the parks increased by a mean of 50%, and was up to 800% higher at fire hotspots (Fig. 2). Previous analyses have demonstrated the strong association between fire and deforestation throughout the Amazon basin[19], but the specific mechanisms through which the transition to post-conflict has

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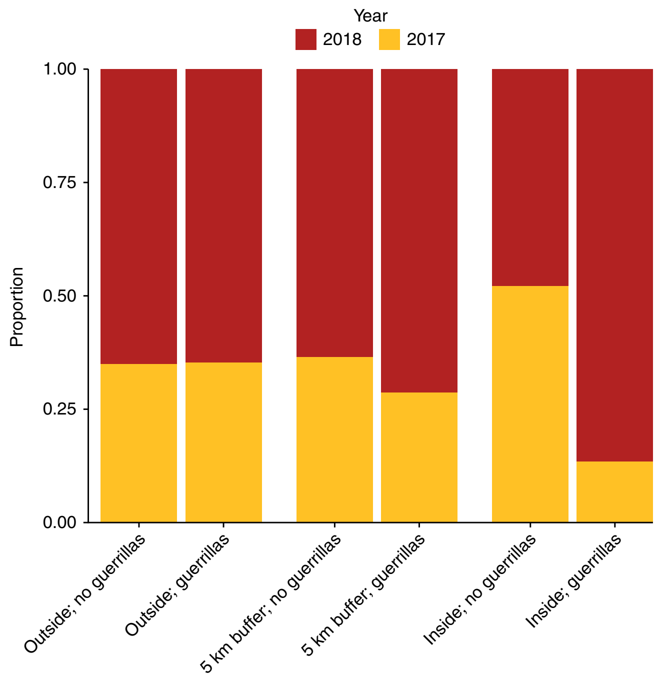

Fig. 1 | Fire occurrence in Colombia. Fires were detected over January and February of each year by the Moderate Resolution Imaging Spectroradiometer (see Methods).

ushered the widespread use of fire can only be inferred based on previous studies.

On-the-ground data on why and how households and individuals choose targets for fire and clearing remain scarce and were limited until recently by guerrilla activity. Nevertheless, analyses of deforestation drivers and trends, particularly in the heavily affected region of the northwestern Amazon, point to two inter-related mechanisms of forest loss in the contested frontiers. At the centre of these mechanisms is the weak government capacity for law enforcement (environmental or otherwise) at the frontier. With demobilization, law enforcement at the frontier is now up for grabs and is open for contest by various actors, from smallholders to ranchers, land speculators and even drug traffickers.

Despite the sustainable development language of the accords, two of its key provisions may directly influence the spike in fires and deforestation. First, the accords promised land titles to former combatants[2], particularly in areas where the guerrillas exerted territorial control, which included several protected areas. While old growth and secondary forests offered cover from air-assisted detection by the government, the advent of peace makes forest cover lose much of its value as a strategic asset. Instead, and in the absence of strong territorial control, demobilization makes the land accessible for cultivation and pasturing by both former combatants who know the regions best and newcomers waiting to cash in on newly accessible land.

Second, another provision of the accords allocates funding to improve tertiary roads throughout former FARC territories. In Colombia, as elsewhere, road construction is one of the primary drivers of deforestation. Previous studies in the Colombian Amazon have shown that roads and fire are linked[12], as urbanization following road improvement creates demand for land in the immediate vicinity of roads[20]. With weak institutions and enforcement, this demand easily translates into land grabs through which smallholder plots become consolidated into large ranches[21]. This process is probably just beginning in the affected protected areas, but the sharp increase in fire frequency in only one year indicates that the window of opportunity for slowing deforestation is rapidly closing.

Unless the land title precedes the establishment of the protected area, clearing the forest or buying and selling land in protected areas is illegal. However, since land tenure is often contested and the central government does not compensate smallholders after declaring a protected area (such as the recent expansion of Chiribiquete National Park)[22], a parallel market for land exists even inside protected areas. Therefore, investments in newly opened frontier lands have the greatest potential to yield profits as roads and development reach them. The result is the transformation of nominally public forests into private, forest-free landholdings.

Contemporary warfare mostly involves within-country conflicts with non-state actors[10], and the negative environmental impacts of such conflicts have been documented around the world[9]. However, relatively little attention has focused on post-conflict situations, such as the one currently unfolding in Colombia. The disproportionate increase in fires from one year to the next indicates vast transformations in the core of multiple protected areas following demobilization.

Peace is an end in itself, and modern conservation requires the involvement of local communities whose displacement by warfare undermines both planning and implementation[9]. In the context of humanitarian and social needs, peace is its own reward, but FARC demobilization has opened a formerly contested frontier to (predominantly illegal) economic development. As development in twenty-first-century Latin America still involves forest clearing on colossal scales[23], environmental sustainability requires proactive enforcement and institutional capacity lacking at the frontier. Since former guerrilla strongholds were overwhelmingly located in far-flung forest frontiers that were largely inaccessible to the institutions and services of the central government, an enforcement vacuum would necessarily accompany guerrilla demobilization unless massive institutional build-up preceded peace with the FARC.

Following massive international investment in forest conservation in Colombia (https://ec.europa.eu/europeaid/countries/colombia_en), this is an important reminder that territorial control involves much more than protected area declarations. Although currently obscured by the spike of fires, the conjunction of FARC demobilization presents several opportunities for forest conservation. The newfound accessibility of the forest frontier need not translate into deforestation if local populations benefit from conserving forests. A focus on real-time monitoring of the kind deployed here, approaches to increase returns to local people, and decentralized governments for maintaining and defending the forest can conserve forests and biodiversity in a more socially sustainable way than the FARC conflict ever could. First, the end of the conflict enables direct payments for ecosystem services beyond the Andean core, such as the United Nations Office on Drugs and Crime programme Familias Guardabosques (Forest Warden Families). At its peak, this direct-payments programme reached about 88,484 families living alongside 100,000 ha of forest, but this previously implemented programme was strictly linked to anti-drug policy[24]. Instead, such a programme across forest frontiers conditional on conservation can build accountability for sustainable development. Second, there is scope to reintegrate combatants into society as stewards of numerous protected areas. FARC guerrillas spent years in the forests and know many protected areas well, so their skills can be deployed for conservation at access points and trails.

Finally, frontier municipalities can constitute a market for deforestation. At present, there are benefits to those who clear the forest and grab land, and costs for the rest of society in the form of altered water and carbon cycles. A domestic market for deforestation permits, similar to the successful US cap-and-trade programmes for NO_x and SO_2, can change the cost–benefit balance to local actors better than the current system. Currently, analyses of emerging

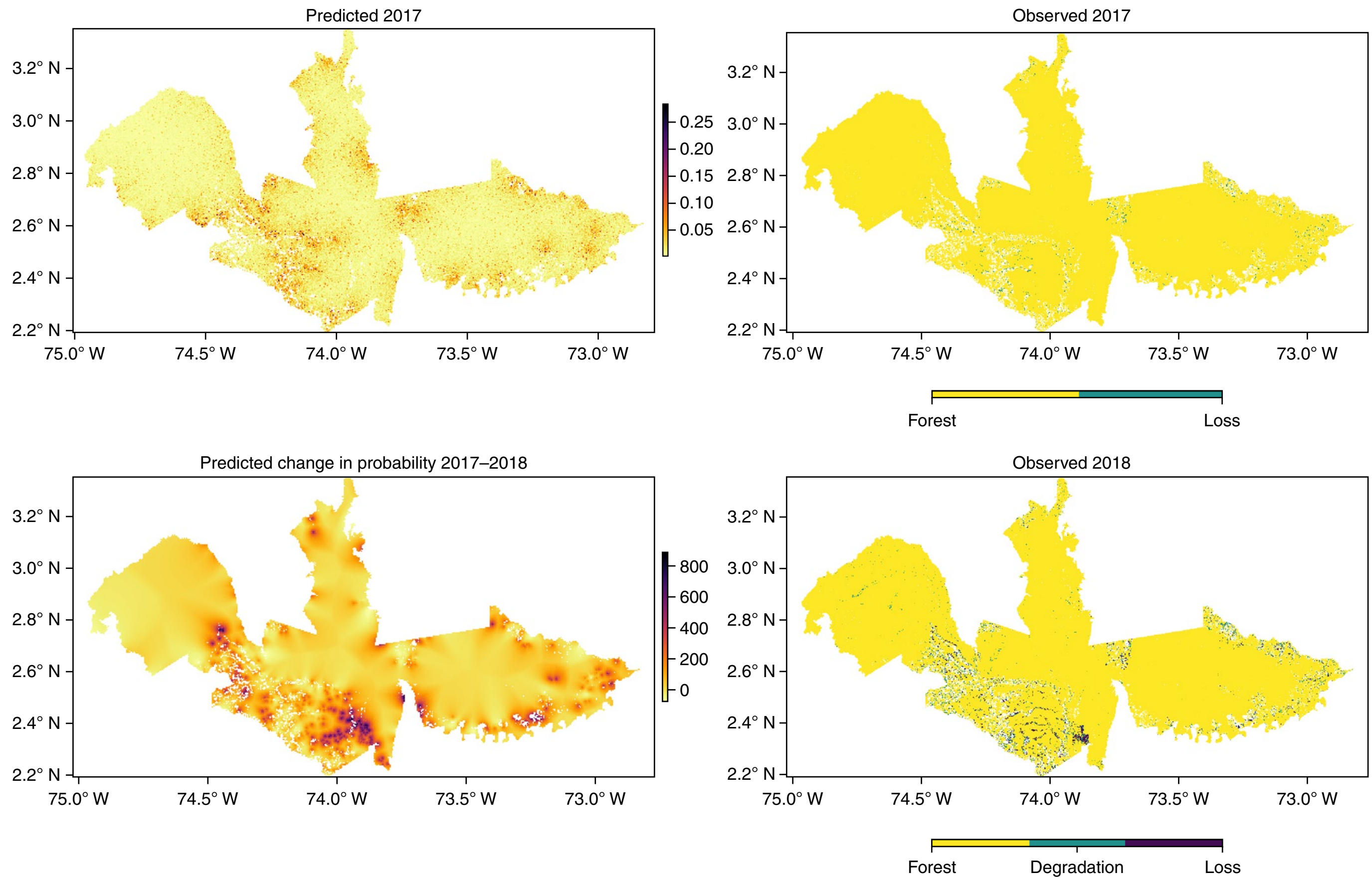

Fig. 2 | Modelled probability and recorded deforestation. Results are shown for 2017 (top) and 2018 (bottom) at three protected areas of the Amazon Andes. The bottom left panel shows the change in the probability of deforestation based on fire frequency from 2017/2018. Observed 2017 is derived from Hansen/UMD/Google/USGS/NASA.

environmental markets are linked to REDD+ (http://mercadosambientalescolombia.com/insumos/publicaciones/), but conditioning local conservation on erratic international markets makes these programmes fragile. Instead, domestic markets for deforestation would offset planned road expansion (another tenet of the peace accords) within municipality-based conservation areas. With a limited number of permits for forest clearing, heavily forested municipalities with low clearing rates could sell their annual permits and thus receive compensation for maintaining the forest. Forest conservation groups could purchase permits and thus limit the total frontier deforestation allowed in a given year.

While elucidating the mechanisms through which FARC demobilization has enabled a new rush of fires into Colombian protected areas will require future interdisciplinary and on-the-ground research, remote sensing data demonstrate that actors on the ground have responded to the power vacuum before any institutional response has coalesced. At the same time, our analyses show the potential for real-time deforestation monitoring, strengthening the prospects for accountability for deforestation on the ground. The time for securing peace with the forest is now.

Methods

Fire detection. We used hotspot detections from the Active Fire product from the Moderate Resolution Imaging Spectroradiometer aboard the Terra and Aqua Satellite (Collection 6). Hence, the availability of high-quality fire data for the first two months of the past two years (peak fire season in Colombia) makes it possible to assess the effects of the 2017 FARC demobilization on forest conservation in real time.

Remote sensing and protected areas. We calculated the distance to the nearest protected area for each fire. Fire density was calculated using the Point Density spatial analyst tool in ArcGIS[25], which calculates the point features around the centre of each raster cell to generate a density per unit area (in this case, in decimal degrees). Protected areas and their limits were obtained from the Colombia Natural National Parks System[25], and a 5 km buffer was constructed for analysis.

Mapping FARC influence. The polygons for the areas under guerrilla control in 2013 were obtained from ref. [26]. For each fire, we indicated its position within or outside territory under guerrilla control.

Statistical analyses. We used three-way association analyses for count data to determine whether the categorical variables 'geographic location' (outside or inside protected areas, or within a 5 km buffer zone), 'year' (2017 versus 2018) and 'former FARC territorial control' (no/yes) influenced the incidence of fires. The fire count data were then analysed to compare complete independence against joint independence and conditional independence among all three predictive variables. In the case of complete independence, the probability of fires in a category of each variable was completely independent of the probability of a given category in another variable. For example, the probability of a fire inside the protected area would be completely independent of either the probability of fire in 2017 or the probability of fire in areas formerly controlled by the FARC. In the case of joint independence of location and year from FARC control, the probability of fires in a category of the location and year variable was jointly independent of the category in FARC control. For example, the probability of a fire inside the protected area may or may not be independent of the probability of a fire in 2017, but either way the resulting joint probability is independent of the probability of fire in areas formerly controlled by the FARC. In the case of conditional independence, the probability of fires by location may appear to depend on the year, but this apparent relationship is entirely explained by FARC control. Additionally, we tested whether the relationship between the probability of fires by location and year was independent of FARC control.

All analyses were run in R language version 3.4.4 (ref. [27]). The glm function with the family=poisson() option and the count of fires as a response variable was used to fit the different models. The anova function was then used to compare the joint independence and conditional independence models against the null (complete independence). The expected probability of the residual deviance of the last model is chi-squared distributed with degrees of freedom of the model residuals. To ensure that any associations detected were not simply the result of a disproportionate share of fires occurring outside protected areas, these analyses were repeated with only the data for the protected areas and their 5 km buffer zone. A summary of the models for all of the data is shown in Supplementary Table 1. Models for the protected area and buffer are summarized in Supplementary Table 2.

Deforestation modelling. To illustrate how the spike of fires in the protected areas discussed here translates into deforestation, we applied a spatial logistic regression model of deforestation as a function of the distance to the nearest fire calibrated with 10 years of fire and deforestation data from the neighbouring Amazonian lowlands of Guaviare[17] to predict the deforestation in the protected areas of Picachos–Tinigua–Macarena associated with the fires observed. Briefly, we used a rasterized layer of the parks to calculate the distance to the nearest fire each year for 2017 and 2018 using the distanceFromPoints function in the raster version 2.6.7 R package. These data (52,232 pixels encompassing ~2,327 km^2) were then filtered for standing forest cover in 2016[23], and included alongside the published data in a spatial logistic regression fitted using INLA package version 17.06.20, while specifying a prediction for the data for the protected area axis. The predicted probability values for 2017 and 2018 were then compared with the ref.[18] deforestation sites for 2017, and the 2018 forest loss interpreted from Landsat images, using the area under the curve of the plot of the true positive rate against the false positive rate, which ranged from 0 to 1, with values closer to 1 corresponding to better models. The ROCR package was used to measure performance and calculate the area under the curve (AUC). The modelled probabilities were converted to binary expected deforestation using the optimal. cutpoints function of the OptimalCutpoints version 1.1-3 package. The cutpoint was estimated with all years of the published Guaviare data as a training set, and using the Maximum Specificity criterion. The percent change in the probability of deforestation was calculated as $(\text{probability}_{2018} - \text{probability}_{2017}) \times 100/\text{probability}_{2017}$.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Data associated with this paper have been deposited in the Dryad digital repository at https://doi.org/10.5061/dryad.8nc8480.

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Author contributions

D.A. contributed to the conceptualization, methodology, data collection, spatial and statistical analyses. L.S. contributed to the conceptualization. L.M.D. contributed to the statistical analyses and policy recommendations. All authors wrote the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41559-018-0727-8.

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☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	An indication of whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
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☒	☐	Clearly defined error bars *State explicitly what error bars represent (e.g. SD, SE, CI)*

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Software and code

Policy information about availability of computer code

Data collection	We acknowledge the use of data and imagery from LANCE FIRMS operated by the NASA/GSFC/Earth Science Data and Information System (ESDIS) with funding provided by NASA/HQ
Data analysis	All analyses ran in the R language v.3.4.4. To predict the deforestation in the protected areas of Picachos-Tinigua-Macarena associated with the fires observed, we used a previously published model of deforestation as a function of distance to the nearest fire, the previously published data and code are available at https://datadryad.org/resource/doi:10.5061/dryad.1925k To predict the deforestation in the protected areas of Picachos-Tinigua-Macarena associated with the fires observed, we used a previously published model of deforestation as a function of distance to the nearest fire17. Briefly, we used a rasterized layer of the parks to calculate the distance to the nearest fire each year for 2017 and 2018 using the distanceFromPoints function in the raster v2.6.7 R package. These data (52,232 pixels encompassing ~2327 km2) were then filtered for standing forest cover in 201623, and included alongside the published data in a spatial logistic regression fitted using the INLA package v.17.06.20, while specifying a prediction for the data for the PA axis. The predicted probability values for 2017 were then compared to the Hansen et al 2013 deforestation sites using the area under the curve (AUC) of the plot of true positive rate against the false positive rate, which ranges from 0 to 1, with values closer to 1 corresponding to better models. The ROCR package was used to measure performance and calculate the AUC.

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Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

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The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information files.

Field-specific reporting

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Analysis of remotely sensed data for the 2017 and 2018 fire season show that fires have increased during the last year . We developed a spatial logistic regression model that predicts commensurate increases of the probability of per-pixel deforestation within the parks by a mean of 52% percent change for 2018.
Research sample	54 terrestrial protected areas and their limits were obtained from the Colombia Natural National Parks System,we excluded 5 areas maritime areas
Sampling strategy	All fire hotspots detections from MODIS were used.
Data collection	We used Hotspot detections from the MODIS sensor aboard Terra and Aqua satellite
Timing and spatial scale	We used Hotspot detections from the MODIS sensor aboard Terra and Aqua satellite for Jan/Feb 2017 and Jan/Feb 2018 (https://firms.modaps.eosdis.nasa.gov/download/). Each MODIS active fire location represents the center of a 1km pixel that is flagged by the algorithm as containing one or more fires within the pixel.
Data exclusions	We excluded Maritime Protected Areas
Reproducibility	All MODIS data can be downloaded from the ANCE FIRMS operated by the NASA/GSFC/Earth Science Data and Information System (ESDIS). The protected area database, the code for data analysis and deforestation prediction is also available.
Randomization	NA
Blinding	NA

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

Materials & experimental systems

n/a	Involved in the study
☒	☐ Unique biological materials
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☒	☐ Animals and other organisms
☒	☐ Human research participants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging