UNIVERSIDAD DE MURCIA

FACULTAD DE BIOLOGÍA

Dynamic Integration of Sustainability Indicators in the Socio-ecological Model of the Fuerteventura Biosphere Reserve.

Integración Dinámica de Indicadores de Sostenibilidad en el Modelo Socio-ecológico de la Reserva de la Biosfera de Fuerteventura.

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Dynamic Integration of Sustainability Indicators in the Socio-ecological Model of the Fuerteventura Biosphere Reserve.

Integración Dinámica de Indicadores de Sostenibilidad en el Modelo Socio-ecológico de la Reserva de la Biosfera de Fuerteventura.

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I. INTRODUCCIÓN Y OBJETIVOS

I.1. Introducción

En los sistemas socio-ecológicos (SES), las variables interactúan de manera no lineal, con mecanismos de realimentación que conectan los distintos sistemas sociales y ecológicos que forman parte de un SES, de modo que evolucionan de manera conjunta (Gunderson y Holling 2002; Ostrom 2009).

La creciente insostenibilidad en la evolución de los sistemas socio-ecológicos ha estimulado la búsqueda de nuevos enfoques que permitan entender la complejidad de los problemas socio-ecológicos, e implementar políticas y medidas más sostenibles (UNEP 2002). Sin embargo, la aplicación real de políticas integrales y sostenibles en estos sistemas está todavía lejos del nivel requerido.

Entre las dificultades que explican la brecha entre el conocimiento y la ejecución de estas políticas encontramos las siguientes: i) Tradicionalmente, las dimensiones social, económica y ecológica han sido consideradas como entidades independientes, lo que ha dado lugar a políticas y medidas inadecuadas, lo que subraya la necesidad de incorporar una perspectiva sistémica para el estudio de los SES. ii) La falta de herramientas adecuadas para el diagnóstico y la evaluación de la opciones de gestión más sostenibles, y que, al mismo tiempo, faciliten la comunicación entre el conocimiento científico, los tomadores de decisiones y otros agentes sociales implicados en relación a los temas clave para la sostenibilidad. iii) La necesidad de sistemas socio-ecológicos que sirvan como áreas de estudio piloto para esas políticas y medidas de sostenibilidad, papel especialmente reconocido para las Reservas de la Biosfera.

Las diferentes dimensiones de la sostenibilidad han de ser consideradas desde un enfoque integral (Meppen y Gill 1998; Floyd y Zubevich 2010), puesto que los enfoques lineales que tradicionalmente han sido usados para la gestión de los SES no han resultado adecuados en términos de sostenibilidad (Bell y Morse 1999; Matysek 2009, Mirchi et al. 2012). La decisión de modificar alguno de los aspectos de los SES puede tener consecuencias inesperadas o a medio plazo, que podrían agravar el problema original o generar otros desafíos. En este sentido, la perspectiva sistémica que ofrecen los sistemas dinámicos (Forrester 1931) representa un marco adecuado para la gestión de sistemas socio-ecológicos complejos y cambiantes (Fong et al. 2009; Kelly et al. 2013).

Para llevar a cabo una planificación y gestión adecuadas en los SES, es esencial disponer de herramientas sencillas que faciliten el estudio de sistemas complejos y la exploración de los efectos a medio y largo plazo en cualquiera de los componentes del sistema y bajo distintas opciones de gestión (Hjorth y Bagheri 2006). Los modelos, descripciones simplificadas de la realidad construidas para facilitar el análisis del sistema real que representan (Blanco 2013; Polo 2013), y concretamente los modelos de simulación dinámica (SDMs), ofrecen numerosas ventajas como herramienta para la gestión, dada su capacidad para facilitar la comprensión de las complejas interacciones propias de los SES y explorar su comportamiento en el largo plazo (Martínez-Moyano y Richardson 2013). Concretamente, la integración de indicadores de sostenibilidad en los modelos de simulación dinámica facilita el entendimiento del comportamiento dinámico del sistema de estudio, las interacciones entre las variables clave y estos indicadores, así como la exploración de las tendencias del sistema a largo plazo, bajo diferentes escenarios y políticas.

Por otro lado, las reservas de la biosfera pueden ser consideradas áreas de estudio piloto para esas políticas y medidas de sostenibilidad. De hecho, la UNESCO (2007) reconoce las reservas de la biosfera como “laboratorios para el desarrollo sostenible”, donde el conocimiento, la investigación, la educación y la participación en los procesos de toma de decisiones son temas clave para el programa MaB, Hombre y la Biosfera (Batisse 1986; Price 2002).

El caso de estudio de esta tesis es la Reserva de la Biosfera de Fuerteventura. Las razones para la selección de una reserva de la biosfera insular son las siguientes: i) Son áreas especialmente vulnerables en cuanto a los recursos naturales, como el agua y la energía; ii) Los sistemas insulares facilitan la evaluación de los flujos de material y energía, dados sus límites físicos; iii) Esos límites favorecen una mayor conciencia sobre la necesidad de un desarrollo sostenible. El sistema socio-ecológico de la Reserva de la Biosfera de Fuerteventura representa un desafío a la hora de compatibilizar un desarrollo turístico creciente con la gestión sostenible de los recursos naturales, en ocasiones escasos y dependientes del exterior (como los recursos hídricos y la energía), y muy vulnerables ante procesos de degradación.

I.2. Objetivos

El objetivo principal de esta tesis es explorar el potencial de una herramienta desarrollada para la evaluación de la sostenibilidad y que puede ser útil para la gestión de sistemas-socioecológicos reales, en este caso la Reserva de la Biosfera de Fuerteventura. Para ello, se ha desarrollado, validado y aplicado un modelo dinámico integral del sistema socio-ecológico de la Reserva de la Biosfera de Fuerteventura, en combinación con otros métodos y enfoques (indicadores, análisis de políticas y escenarios, evaluación de la incertidumbre), conformando una herramienta para llevar a cabo análisis prospectivos y facilitar los procesos de toma de decisiones.

De forma más concreta, los objetivos de esta tesis doctoral son los siguientes:

1. Desarrollar un modelo dinámico integral de un sistema socio-ecológico (SES), la Reserva de la Biosfera de Fuerteventura, que incluya variables y procesos clave con el fin de entender su dinámica a través de una serie de indicadores de sostenibilidad integrados en el modelo, propuestos por el Plan de Acción de la Reserva y otros actores sociales. Así mismo, se pretende validar el modelo desarrollado a través de diversos procedimientos de validación, ampliamente utilizados para este tipo de herramientas.

2. Analizar los principales cambios acontecidos en el sistema socio-ecológico de la Reserva de la Biosfera de Fuerteventura, así como las interacciones entre diferentes variables claves e indicadores de sostenibilidad.

3. Aplicar el modelo dinámico para la sostenibilidad de la Reserva de la Biosfera de Fuerteventura (FSM) para evaluar cómo se comportan determinados indicadores de sostenibilidad bajo una serie de medidas de gestión ambiental, propuestas por diversos agentes sociales, y cuantificar el grado de cumplimiento de los objetivos ambientales

que incluye el Plan de Acción de la Reserva. Además, se pretende priorizar entre esas medidas ambientales utilizando esos indicadores y sus umbrales de sostenibilidad, e identificar efectos secundarios y posibles contradicciones entre esos objetivos ambientales, así como detectar posibles objetivos que no se abordan con las medidas analizadas.

4. Aplicar un amplio análisis de sensibilidad al FSM con el objetivo de mejorar la estructura del modelo, llevar a cabo una evaluación detallada de la robustez de los resultados e identificar puntos clave del modelo sobre los que definir medidas de gestión eficaces.

5. Incorporar el análisis de incertidumbre en la evaluación de los resultados de simulación del modelo bajo distintas opciones y políticas, así como en el análisis de la vulnerabilidad de este sistema socio-ecológico a ciertos cambios ajenos al mismo, como escenarios económicos y climáticos.

6. Emplear el modelo dinámico para la sostenibilidad de la Reserva de la Biosfera de Fuerteventura para llevar a cabo un análisis detallado de la dinámica del hábitat potencial de la houbara canaria (*Chlamydotis undulata fuerteventurae*), identificar los factores de amenaza que más están contribuyendo a la pérdida del hábitat en el periodo reciente (1996-2011) y evaluar los efectos que distintas medidas de gestión y escenarios económicos pueden tener sobre sobre el hábitat potencial de la hubara en el futuro.

II. METODOLOGÍA

II.1. Caso de estudio

La isla de Fuerteventura es la segunda más extensa del Archipiélago Canario, con unos 1.655 Km^2, incluyendo la Isla de Los Lobos. El clima dominante en la isla es el desértico hiperárido infra-termomediterráneo (Torres Cabrera 1995). La vegetación de sustitución es la que actualmente predomina, con matorrales xerofíticos (dominados por *Launaea arborescens*, *Lycium intricatum*, *Salsola vermiculata*, *Suaeda* spp. y *Euphorbia* spp.) y pastizales anuales, frecuentemente degradados y donde pequeños parches de vegetación nativa están relegados a áreas casi inaccesibles (Rodríguez-Rodríguez 2005; Schuster et al. 2012). Por otro lado, el carácter insular favorece una amplia variedad de especies endémicas de flora y fauna, con un grado de endemismo alrededor del 5% (Arechevaleta et al. 2010). De hecho, Fuerteventura cuenta con 6 áreas importantes para la flora amenazada española y una excepcional, la Península de Jandía (del Valle et al. 2004).

En relación a sus paisajes, la mayoría de ellos son paisajes culturales marcados por la aridez y la gestión tradicional del agua y la tierra. Claro ejemplo de ello son las gavias, agrosistemas que favorecen la concentración natural de nutrientes y humedad en el suelo (Díaz et al. 2011). En las últimas décadas, las actividades productivas tradicionales (ganadería, pesca artesanal y cultivo de secano) han sido mayoritariamente sustituidas por las actividades turísticas y las ramas productivas asociadas. Por tanto, el turismo ha representado el principal motor de los cambios socioeconómicos y ambientales de la Reserva en los últimos años (Fernández Palacios y Whittaker 2008; Santana-Jiménez y Hernández 2011), dando lugar a la aparición de nuevas exigencias socio-ecológicas, que han de ser ampliamente abordadas.

Fuerteventura es un área singular dentro de la Red Mundial de Reservas de la Biosfera, declaración aprobada por la UNESCO en 2009, configurando una de las zonas desérticas y semidesérticas más grandes de la Unión Europea, por lo que su vulnerabilidad ante esas exigencias agudiza esa necesidad.

II.2. Modelos de simulación dinámica

La metodología de los sistemas dinámicos, desarrollada inicialmente por Forrester (1961, 1994), tiene un enorme potencial para su aplicación en la gestión sostenible de los SES y la toma de decisiones, dada su capacidad para la comprensión del comportamiento dinámico del sistema y para entender las interrelaciones entre las distintos procesos. Además, los modelos de simulación dinámica (SDMs) permiten la evaluación del sistema bajo distintos escenarios futuros y, por tanto, anticipar las consecuencias a medio y largo plazo de posibles medidas y estrategias de gestión (Kelly et al. 2013; Voinov y Shugart 2013).

Por otro lado, los indicadores también se consideran un componente esencial de la evaluación de la sostenibilidad, puesto que representan una herramienta razonablemente sencilla que permite reducir la complejidad de los procesos que representan y facilitan su seguimiento, así como la comunicación con otros actores sociales afectados por dichos procesos, y las decisiones que se toman al respecto (Lotze-Campen 2008; Singh et al. 2012; Poveda and Lipsett 2014). Sin embargo, numerosos autores señalan la falta de utilidad real de los catálogos de indicadores en los procesos de adopción y evaluación de medidas de gestión aplicables a sistemas como las reservas de la biosfera (Reed et al. 2006; Levrel et al. 2009; Kajikawa et al. 2011). Por un lado, se apunta la necesidad de que los indicadores sean dinámicos, es decir, que reflejen los continuos cambios que experimentan los procesos que representan. Por otro lado, es necesario disponer de umbrales que permitan cuantificar si los cambios sufridos por los indicadores son aceptables o no en términos de sostenibilidad (Lancker and Nijkamp 2000; Moldan et al. 2012).

En este trabajo se presenta un modelo dinámico de sostenibilidad para la Reserva de la Biosfera de Fuerteventura, desarrollado bajo el enfoque de los sistemas dinámicos (Meadows et al. 1972; Forrester 1961; Ford 1999; Sterman 2000; Jørgensen and Fath 2011; Martínez-Moyano and Richardson 2013). El modelo, validado para el periodo 1996-2011, permite la integración de una serie de indicadores de sostenibilidad, propuestos por el Plan de Acción de la Reserva de la Biosfera de Fuerteventura y otros expertos, así como distintas aplicaciones (explicadas en detalle en los capítulos 4, 5 y 6) como herramienta para la gestión y la toma de decisiones.

III. INTEGRACIÓN DINÁMICA DE INDICADORES DE SOSTENIBILIDAD EN SISTEMAS SOCIO-ECOLÓGICOS INSULARES

En este capítulo se presenta un modelo dinámico integral, el modelo dinámico para la sostenibilidad de la Reserva de la Biosfera de Fuerteventura (FSM), validado y calibrado para el periodo 1996-2011. El FSM incluye 520 variables, de las cuales 22 representan variables de estado y 37 son indicadores de sostenibilidad (propuestos por la propia

Reserva y otra literatura científica). Se estructura en 5 sectores: el socio-turístico, el de usos del suelo, el de la biodiversidad, el de calidad ambiental y el de los recursos hídricos. El modelo ha superado varios test de verificación (la simulación del modelo más allá de los límites temporales para el que ha sido construido, tests de consistencia dimensional, 25 tests de condiciones extremas, análisis de sensibilidad y tests de comparación con series de datos observadas para las 20 variables de las que se dispone de datos observados).

El FSM facilita una evaluación integral y dinámica de los principales componentes de este sistema socio-ecológico y sus cambios a lo largo del tiempo, así como la interacción entre los indicadores de sostenibilidad integrados en el modelo y otras variables del sistema.

Los resultados de la simulación mostraron la existencia de contradicciones potenciales ("trade-offs"), no solo entre objetivos de desarrollo socio-económico y de conservación, sino también entre objetivos ambientales bajo distintas opciones de gestión. En este sentido, algunas medidas de conservación orientadas a reducir la degradación de la vegetación potencial, de alta calidad, mediante la limitación del pastoreo podría afectar negativamente a algunas especies amenazadas de carroñeros, como el guirre real (*Neophron percnopterus*), puesto que los restos del ganado representan la base de su dieta. El binomio agua-energía también ofrece otra de estas contradicciones en cuanto al desarrollo sostenible, dada la fuerte dependencia entre el suministro de agua y el consumo de energía.

El FSM se ha mostrado útil como herramienta para mejorar el diagnóstico del sistema bajo estudio, así como para la identificación de "trade-offs" entre indicadores de sostenibilidad, que permitan orientar las políticas y medidas de gestión de este sistema socio-ecológico.

Este capítulo ha sido parcialmente publicado en las revistas científicas Ecosistemas (Banos-González et al. 2013) y Ecological Modelling (Banos-González et al. 2015).

IV. UTILIZACIÓN DE INDICADORES DE SOSTENIBILIDAD DINÁMICOS EN LA EVALUACIÓN DE MEDIDAS AMBIENTALES EN LAS RESERVAS DE LA BIOSFERA

En este capítulo se ha aplicado el FSM para la evaluación del Plan de Acción de la Reserva de la Biosfera de Fuerteventura (AP), en relación a algunos de los principales objetivos de sostenibilidad ambiental (el mantenimiento del paisaje y la vegetación de alta calidad; la rehabilitación de tierras de cultivo tradicionales abandonadas; la minimización de la importación de forraje; la reducción de la dependencia de fuentes de energía alóctona y no renovable y la conservación de especies clave). Para ello, se analizan ocho medidas orientadas a alcanzar dichos objetivos de sostenibilidad ambiental del Plan de Acción (como son la producción renovable del agua, la reducción de la presión ganadera, la rehabilitación de gavias o la reducción de las necesidades de importación de forraje), y se han utilizado diez indicadores de sostenibilidad integrados en el FSM, también propuestos por el Plan de Acción. Además, se ha determinado el grado de incertidumbre asociado a cada resultado. El comportamiento de estos indicadores bajo dichas medidas permite determinar el grado de cumplimiento de esos objetivos a lo largo del periodo 2012-2025. Los resultados de la simulación muestran que, aunque estas medidas mejorarían algunos de los indicadores, ciertos efectos negativos en otros indicadores confirman la existencia de contradicciones (“trade-offs”) entre los propios objetivos de sostenibilidad. En este sentido, por ejemplo, una medida dirigida a mejorar la proporción de vegetación de alta calidad, afectaría negativamente a otros de los indicadores, como la proporción de guirre real, que llegaría a superar su umbral de sostenibilidad.

La definición de umbrales para cada indicador permite a los gestores el establecimiento de una estrategia de priorización entre las ocho medidas analizadas. Los resultados de la simulación han mostrado que algunas de esas medidas son insuficientes para alcanzar ciertos objetivos ambientales, ya que los indicadores que permiten cuantificar su grado de cumplimiento exceden sistemáticamente sus umbrales de sostenibilidad. Este es el caso del indicador del paisaje, la proporción de energías renovables, el consumo de energía primaria per cápita y el indicador de emisión de CO_2 per cápita.

Centrando el análisis en los otros seis indicadores estudiados (la proporción de vegetación de alta calidad, el indicador de sobrepastoreo, la proporción de gavias activas, la proporción de forraje importado, la proporción de hábitat de hubara y la proporción de guirre real), y siguiendo la norma “Umbral superado, medida desechada”, siete de las ocho medidas excederían alguno de los umbrales y, por tanto, su puesta en práctica debería evitarse. Solo una de las opciones, orientada a la producción de forraje rehabilitando gavias abandonadas para alimentar al ganado, no superaría ninguno de estos seis umbrales. Sin embargo, esta medida también presenta ciertos efectos negativos sobre algunos indicadores relacionados con especies bandera, concretamente sobre el hábitat de la hubara canaria y sobre la población de guirre real, por lo que se requerirían algunas medidas compensatorias para su puesta en práctica.

En definitiva, este capítulo demuestra la aplicación de herramientas integrales que permiten: i) analizar medidas propuestas por diferentes actores sociales y planes de acción, ii) cuantificar sus efectos en cuanto a los umbrales de sostenibilidad de una serie de indicadores seleccionados, iii) determinar el grado de incertidumbre de los resultados de la simulación, iv) priorizar entre las medidas analizadas y v) identificar algunos objetivos que no llegan a ser abordados por las medidas propuestas.

Este capítulo se encuentra en revisión en la revista *Ecological Indicators*.

V. APLICACIÓN DEL ANÁLISIS DE SENSIBILIDAD EN MODELOS SOCIO-ECOLÓGICOS (DESDE EL DESARROLLO DEL MODELO A LA EVALUACIÓN DE MEDIDAS DE GESTIÓN)

La evaluación de los sistemas socio-ecológicos sufre generalmente un elevado grado de incertidumbre. El análisis de esta incertidumbre es esencial en los procesos de modelización con el fin de proporcionar a los gestores y tomadores de decisiones una imagen real de los posibles resultados. En este capitulo, se ha aplicado un extenso análisis de sensibilidad (AS) en distintas etapas del desarrollo del modelo dinámico de la sostenibilidad de la Reserva de la Biosfera de Fuerteventura, así como en la aplicación del mismo.

Este análisis de sensibilidad ha permitido abordar distintos objetivos en relación con la mejora y aplicación del modelo, que se sintetizan a continuación:

- La mejora de la formulación del modelo, al eliminar los 8 parámetros considerados insensibles, aplicando un análisis de sensibilidad local (OAT, "One factor at a time").
- Una evaluación detallada de la robustez de los resultados del modelo a través de simulaciones Monte Carlo (MC). Los resultados de MC mostraron una respuesta entre baja (variación por debajo del 50% respecto al valor medio) y moderada (variación entre el 50% y el 100% respecto al valor medio) para dieciseis de las dieciocho variables clave del modelo, lo que respalda la confianza en los resultados del mismo.
- La identificación de puntos de cambio ("leverage") a través del OAT, y su aplicación para la definición de posibles medidas de gestión. Los resultados apuntan a una mayor eficacia de las medidas basadas en estos puntos "leverage", respecto a otras medidas propuestas por distintos actores en relación con la conservación de la vegetación de alta calidad, así como en relación con el control del desarrollo urbano-turístico.
- La incorporación de la incertidumbre en la evaluación de ciertas políticas y medidas. En este sentido, los resultados de las simulaciones Monte Carlo han mostrado diversos casos de indicadores en los que el valor medio de las simulaciones no supera el umbral de sostenibilidad, mientras que si se tiene en cuenta la incertidumbre (intervalo de confianza del 95%), dicho umbral podría llegar a ser superado. Por ejemplo, el número de indicadores que superan sus umbrales pasaría de 2 a 4 indicadores de los 7 analizados bajo la simulación tendencial (BAU). Bajo la Política I (limitación de nuevos alojamientos turísticos), el número de indicadores que exceden sus umbrales pasaría de 1 a 3, mientras que bajo la Política II (reducción del pastoreo), ese número pasaría de 3 a 4. Por lo tanto, la superación de algunos umbrales podría haber pasado desapercibida si la incertidumbre no se tiene en cuenta.
- El análisis de cómo afecta la incertidumbre al estudio de la vulnerabilidad del sistema bajo ciertos cambios ajenos al mismo, como pueden ser distintos escenarios económicos y climáticos. En este sentido, la vulnerabilidad del sistema podría ser mayor que la percibida cuando solo se consideran los valores medios, puesto que el número de indicadores que supera su umbral de sostenibiliad aumenta cuando se tiene en cuenta la incertidumbre.
- Los resultados de la simulación bajo los dos escenarios de cambio climático considerados (A2 y B2), muestran que el número de indicadores cuyo valor medio superaría su umbral de sostenibilidad aumentaría de 2 a 3 de los 7 indicadores analizados. Aunque preliminares, los resultados apuntan a la potencial vulnerabilidad de este sistema insular hiperárido al cambio climático.
- Por otra parte, algunos de los resultados preliminares del MC para los indicadores analizados hasta 2025, sugieren que el sistema socio-ecológico de Fuerteventura podría ser más reactivo a la intervención y las medidas de gestión, que a los cambios económicos externos. En el caso del indicador de artificialización del territorio, éste cambiaría entorno a un 4%-7% bajo los escenarios económicos analizados, pero se reduciría hasta un 46% bajo una de las medidas propuestas en base a uno de los

leverage-points, destinada al control del crecimiento de las infraestructuras turísticas. Esto subraya la responsabilidad de los gestores y tomadores de decisiones para abordar medidas que contribuyan a un desarrollo más equilibrado y sostenible para Fuerteventura.

VI. MODELIZACIÓN DINÁMICA DE LA PÉRDIDAD POTENCIAL DEL HÁBITAT DE ESPECIES AMENAZADAS: EL CASO DE LA HUBARA CANARIA (*CHLAMYDOTIS UNDULATA FUERTEVENTURAE*)

El modelo dinámico para la sostenibilidad de la Reserva de la Biosfera de Fuerteventura (FSM) ha sido aplicado al análisis de la pérdida del hábitat de una de las especies bandera de la isla: la hubara canaria (*Chlamydotis undulata fuerteventurae*). Esta herramienta ha permitido la evaluación de los efectos fruto de la interacción entre la dinámica socio-económica y ambiental de Fuerteventura sobre los factores de amenaza del hábitat de esta especie, así como la posibilidad de llevar a cabo análisis prospectivos.

Los resultados de la simulación muestran una pérdida del hábitat alrededor del 13% a lo largo del periodo 1996-2011, siendo los factores que más contribuyen la ocupación del suelo para urbanizar y la construcción de nuevas carreteras y caminos.

Bajo el escenario tendencial (BAU), se perdería alrededor de un 20% del hábitat al final del periodo de simulación (2012-2025). El impacto del escenario de crecimiento económico sobre el hábitat, supondría una pérdida adicional del 13% respecto al BAU, mientras que bajo un escenario de recesión económica, la pérdida sería un 12% menor que la esperada bajo BAU. Una política de rehabilitación de gavias supondría una pérdida adicional de casi un 6% respecto al BAU. Esto sugiere la existencia de un "trade-off" entre la recuperación de los servicios ecosistémicos que ofrece la rehabilitación de gavias y la conservación del hábitat de la hubara, puesto que las gavias abandonadas representan hábitat secundario de esta especie. "Trade-offs" como el señalado deben ser abordados en los procesos de gestión, así como la inclusión de medidas compensatorias que garanticen los objetivos de conservación.

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VII. CONCLUSIONES

1. Como contribución a la evaluación de la sostenibilidad de sistemas socio-ecológicos insulares, un modelo dinámico de la sostenibilidad de la Reserva de la Biosfera de Fuerteventura (FSM) ha sido desarrollado y calibrado para el periodo 1996-2011. El FSM contiene 520 variables, 22 de las cuales representan variables de estado, y se estructura en 5 sectores: el socio-turístico, el de usos del suelo, el de la biodiversidad, el de calidad ambiental y el de los recursos hídricos. El FSM superó varios test de bondad del ajuste con excelente (MAPE y NRMSE por debajo del 10%) o buen grado de ajuste (MAPE y NRMSE entre 10% y 20%) para la mayoría de las 20 variables con series de datos observados disponibles. Este y otros test de validación, como 25 tests de condiciones extremas, 25 simulaciones más allá del límite temporal para el que fue construido el modelo y el test de consistencia dimensional, respaldan la

utilidad del modelo como una herramienta de comprensión y diagnóstico de este sistema socio-ecológico (SES) y su sostenibilidad.

2. El modelo ha permitido la integración de 37 indicadores de sostenibilidad, que facilitan una evaluación integral y dinámica del sistema, así como el análisis de las interacciones entre variables clave e indicadores. Los resultados ponen de manifiesto la efectividad de la utilización de herramientas dinámicas como el FSM para identificar y cuantificar potenciales contradicciones ("trade-offs"), no solo entre objetivos de desarrollo socioeconómico y ambientales, sino también entre objetivos estrictamente ambientales. Por ejemplo, entre la conservación de la vegetación de alta calidad y la conservación de especies de carroñeros amenazadas; o entre la demanda de agua desalada y el consumo de energía per cápita. Estos "trade-offs" podrían haber pasado desapercibidos si sólo se hubiesen utilizado catálogos estáticos de indicadores.

3. El FSM ha sido aplicado a la evaluación del Plan de Acción de la Reserva de la Biosfera de Fuerteventura (AP), en relación a algunos de los objetivos de sostenibilidad (el mantenimiento del paisaje y la vegetación de alta calidad; la rehabilitación de tierras de cultivo tradicionales abandonadas; la minimización de la importación de forraje; la reducción de la dependencia de fuentes de energía alóctona y no renovable y la conservación de especies clave), los indicadores y las medidas de gestión propuestas, así como la coherencia entre ellas. Las ocho medidas analizadas están principalmente relacionados con la producción renovable de agua, la reducción de la presión ganadera, la rehabilitación de gavias y la reducción de las necesidades de importación de forraje. Para ello, se ha analizado el comportamiento de diez de los indicadores integrados en el FSM, y para los que se establecieron sus respectivos umbrales de sostenibilidad. Se ha explorado el comportamiento de estos diez indicadores bajo las mencionadas medidas de gestión para el periodo 2012-2025. Los resultados han mostrado que algunos objetivos no serían alcanzados bajo ninguna de las medidas consideradas, puesto que los cuatro indicadores que permiten cuantificar su grado de cumplimiento excederían sistemáticamente sus umbrales de sostenibilidad. Estos cuatro indicadores son: el indicador del paisaje, la proporción de energía renovable, la energía primaria per cápita y las emisiones de dióxido de carbono per cápita. Por lo tanto, se puede concluir que las medidas analizadas, derivadas del Plan de Acción de la Reserva, serían insuficientes a la hora de abordar algunos de sus objetivos ambientales clave, como los relacionados con el paisaje y la energía. Por consiguiente, se deberían adoptar estrategias más ambiciosas para alcanzar estos objetivos, en línea con las propuestas de la Unión Europea en materia de energías renovables.

4. Los resultados de la simulación han permitido establecer una priorización entre las medidas de gestión analizadas, en base a los restantes seis indicadores (la proporción de vegetación de alta calidad, el indicador de sobrepastoreo, la proporción de gavias activas, la proporción de forraje importado, la proporción de hábitat de hubara y la proporción de guirre real) y sus umbrales. De las ocho medidas analizadas, siete de ellas superan alguno de estos umbrales. Aplicando la norma "umbral superado, medida desechada", solo bajo una de las medidas, orientada a la producción de forraje para alimentar al ganado rehabilitando gavias abandonadas, ninguno de estos seis umbrales se vería superado. De este modo, a esta medida se le podría asignar la prioridad más alta entre las medidas analizadas. Sin embargo, esta opción presentaría ciertos "trade-offs" entre algunos de los indicadores estudiados. Por ejemplo, la medida afectaría a la

proporción de población de guirre, puesto que los restos del ganado suponen la base de su dieta, por lo que deberían incorporarse algunas medidas compensatorias.

5. Se ha demostrado que el análisis de sensibilidad (AS) es una importante herramienta en el desarrollo y aplicación de modelos socio-ecológicos, para gestores y usuarios finales. En cuanto a la construcción del modelo, el AS ha permitido la mejora de la formulación y estructura del modelo a partir de análisis de sensibilidad local en los que se analiza un parámetro cada vez ("One factor at a time", OAT). Este análisis ha facilitado la eliminación de ocho parámetros insensibles para las variables clave del modelo, haciendo el modelo más compacto. El AS también ha permitido llevar a cabo una evaluación detallada de la robustez del modelo. La simulación Monte Carlo (MC) mostró una respuesta entre baja (variación por debajo del 50% respecto al valor medio) y moderada (variación entre el 50% y el 100% respecto al valor medio) para dieciseis de las dieciocho variables clave del modelo, lo que respalda la confianza en los resultados del modelo.

6. En relación con la aplicación del modelo y, más concretamente, con la definición de políticas y medidas de gestión, el AS también ha permitido la identificación de puntos de cambio ("leverage points") en el FSM, es decir, los parámetros para cuyo cambio el modelo exhibe una respuesta mayor. Los resultados muestran el potencial de estos puntos de cambio para desarrollar medidas más efectivas que otras medidas propuestas por diferentes actores para un mismo objetivo. La mayor efectividad de medidas basadas en estos parámetros ha sido demostrada para el objetivo de reducción de la degradación de la vegetación de alta calidad y el paisaje, así como para el control del desarrollo urbano-turístico.

7. El AS ha permitido incorporar explícitamente la incertidumbre a la evaluación de políticas y escenarios. Las conclusiones sobre si ciertos objetivos podrían ser alcanzados o si ciertos umbrales podrían ser excedidos, podrían verse alteradas cuando se tiene en cuenta la incertidumbre. Las simulaciones Monte Carlo aplicadas a medidas basadas en los puntos "leverage" identificados mostraron que para ciertos indicadores, sus umbrales de sostenibilidad no se verían sobrepasados considerando los valores medios de la simulación, pero podrían superarse si se tiene en cuenta la incertidumbre con un intervalo de confianza del 95%. De los 7 indicadores analizados, el número de indicadores que superan sus umbrales pasaría de 2 a 4 bajo la simulación tendencial (BAU). Bajo la Política I (limitación de nuevos alojamientos turísticos), el número de indicadores que exceden sus umbrales pasaría de 1 a 3, mientras que bajo la Política II (reducción del pastoreo), ese número pasaría de 3 a 4, de los 7 indicadores considerados. Por tanto, el riesgo potencial de que algún umbral de sostenibilidad pudiera superarse bajo las medidas analizadas podría pasar desapercibido si la incertidumbre no se hubiera considerado. Conclusiones similares han sido extraídas de la evaluación preliminar de la vulnerabilidad del SES ante cambios externos al sistema, como los escenarios socio-económicos y climáticos.

8. Bajo los dos escenarios de cambio climático considerados (A2 y B2), el número de indicadores cuyo valor medio superaría su umbral aumentaría de 2 a 3 de los 7 indicadores analizados. Aunque preliminares, estos resultados apuntan a la potencial vulnerabilidad de este sistema insular hiperárido al cambio climático.

9. Los resultados en relación con las medidas de gestión y escenarios analizados sugieren que el sistema socio-ecológico de Fuerteventura podría mostrarse más reactivo a la intervención política que a ciertos cambios económicos externos al sistema. Algunos indicadores reflejan esta conclusión. Este es el caso, por ejemplo, de la proporción de suelo artificial que cambia entre un 4% y un 7% respecto a BAU bajo los escenarios económicos, pero cuyo incremento es hasta un 46% inferior respecto al BAU bajo medidas de control del índice de ocupación turística. Esto pone de manifiesto la responsabilidad de los gestores y tomadores de decisiones a la hora de abordar medidas que contribuyan a un desarrollo más equilibrado y sostenible para Fuerteventura.

10. En cuanto a la dinámica del hábitat potencial de la hubara canaria, los resultados de la simulación son consistentes con las estimaciones disponibles para los años 1996, 2002 y 2011, con una pérdida alrededor del 13% a lo largo del periodo 1996-2011. El escenario tendencial (BAU) supondría una pérdida de casi el 20% del hábitat entre 2012-2025. Esta pérdida sería alrededor de un 13% mayor y un 12% menor que BAU, bajo los escenarios de crecimiento y recesión económica, respectivamente. Por otro lado, el uso del modelo ha permitido la identificación de contradicciones entre medidas de conservación del hábitat de la hubara y otras políticas ambientales, como la de rehabilitación de las gavias, puesto que las gavias abandonadas forman parte del hábitat secundario de la hubara canaria.

CHAPTER 1

Introduction and Objectives

1. INTRODUCTION AND OBJECTIVES

1.1. INTRODUCTION

1.1.1. Socio-ecological systems and sustainability

Social-ecological systems (SES) can be defined as integrated systems of ecosystems and human society with reciprocal feedback and interdependence (Anderies et al. 2004; Halliday and Glaser 2011; Vugteveen et al. 2015). In complex systems, SES variables interact in a nonlinear fashion characterized by their reinforcing mechanisms, which tie the social and ecological system together in patterns of co-evolution (Berkes and Folke 1998; Gunderson and Holling 2002; Ostrom 2009). In the context of SES, a systemic change can be defined as a fundamental change in the interactions within a system, arising either from an external hazard event or from gradual endogenous change, which leads to a shift in the state of the system to another with new properties (Kinzig et al. 2006; Filatova and Polhill 2012). According to Ropero et al. (2014), when a hazard event occurs or a component undergoes gradual change, the change can be propagated through the entire system by means of cause–effect interactions between the components of the SES. The interacting components form a complex and dynamic entity, the analysis of which requires a holistic approach (Hodbod and Adger 2014).

Sustainability is a contingent term, a moving target which is continuously getting enhanced as our understanding of the system improves (Ko 2005; Hjorth and Bagheri 2006). The sustainability concept gained its official recognition in 1987 with the Brundtland report, defining it as “the development that meets the needs of the present generation without compromising the ability of future generation to meet their own needs” (WCED 1987).

Unsustainable trends in the evolution of social and ecological systems have stimulated a search for new approaches to understand complex problems of environment and development (UNEP 2002). There is an increasing awareness about the need to move faster forward the implementation of more sustainable policies and measures. Despite this, the real application of sustainable policies in socio-ecological systems is quite far from required.

Several barriers and difficulties explain this gap between knowledge and action. One mayor obstacle is that, despite the increasing acknowledgement of the close inter-dependencies between the economic, environmental and social sides, in practice these dimensions are frequently considered in a separated way. One important reason for that is the complex nature of socio-ecological systems. The result is that the information used to manage increasingly complex socio-ecological systems is also increasingly inadequate. This points to the need of a more integrated, systemic perspective of socio-ecological systems. A second problem is the lack of adequate tools to understand, assess and communicate the best options for more sustainable systems and to share visions among policy makers, stakeholders and other agents regarding key sustainability issues, based on sound scientific knowledge. Finally, there is a need for socio-ecological systems which can serve as demonstration pilots for these policies towards sustainability, a role which is explicitly recognized to the Biosphere Reserves. In the following sections these three needs are discussed in detailed.

1.1.2. Why is the systemic perspective needed?

Sustainable development is now a generally endorsed principle whose nature and practice is multidimensional and complex (Nguyen et al. 2011). However, traditionally socio-economical and ecological spheres have been viewed as predominantly disparate entities. The sustainability concept has been based on three key pillars: economic, environmental and social dimensions (Nguyen et al. 2011). A fourth institutional pillar was added by the UN Commission on Sustainable Development, because of the indispensable role of institutions in implementing social, economic and environmental objectives (Mirshojaeian Hosseini and Kaneko 2011). The various dimensions of sustainability need to be considered in an integral approach as suggested by various authors (Meppem and Gill 1998; Floyd and Zubevich 2010). From this point of view, a linear approach to sustainable development has represented one of the major impediments to sustainability (Bell and Morse 1999; Matysek 2009).

To manage complex socio-ecological systems using linear causal thinking may provide unrealistic or, at least, questionable results (Mirchi et al. 2012). As described along the previous paragraphs, the assessment of SES needs to face several difficulties, such as lack of information, sometimes partial, sometimes with different error degree or uncertainty and the difficulty to achieve a right comprehension of the integral behaviour and the non linear relations between variables. Moreover, the decisions to modify any aspect of a SES may have unintended consequences, perhaps with time delays, which may aggravate the original problem or create more challenging issues.

In this sense, the systemic perspective of the system dynamics (SD) provides a framework for managing change and complexity by understanding the dynamic feedbacks embedded in complex systems (Fong et al. 2009).

1.1.3. Tools for assessing and moving forward sustainability

For Hjorth and Bagheri (2006), to do a good planning and management is essential to find a way to formulate reality as a system rather than as a set of independent problems. Thus, any tool to simplify the study of complex system and to predict the effects of changes in any of their components is helpful both in research and in the management of socio-ecological systems (Blanco 2013).

However, this integral approach application in practice seems to be still scarce (Becker and Jahn 1999; Smith et al. 2007), particularly in relation to the application of quantitative approaches to SES (Anderies et al. 2004; Janssen 2006). Most of studies of socio-ecological systems are based on qualitative perspectives and methodologies but, as Duffi et al. (2001) has pointed out, there is a “critical need” for the development of quantitative models that integrate physical, biological, and human systems to address a wide range of socio-ecological issues.

A model is a theory of behaviour (Forrester 1994). Models are formal and simplified descriptions of reality that are built to analyse some aspects of the real system to emulate (Blanco 2013; Polo 2013). Their usefulness lies on facilitating the users to learn about the system which the model represents and to make management decisions, without being needed to deal with the whole complexity. According to Akhtar et al. (2013), the challenge to integral assessment modelling is to capture the sufficient depth of individual system components without compromising breadth of the overall system.

However, is it possible to develop integral quantitative models of SES, to understand the whole dynamics of the system? What type of applications might this type of models have?

System dynamics is a thinking-models and simulation methodology that was specifically developed to support the study of the dynamic behaviour of complex systems (Hjorth and Bagheri 2006). The SD methodology, developed by Forrester (1961) and initially applied in industrial and business systems management, has been refined over the last decades and applied to a broad range of studies, as will be shown in Chapter 2. SD and its principles of feedback and side effects has helped many managers to think about how a strategy might or might not work, and what kind of consequences—intended or unintended— emerge.

Another important feature of SD is its context-specific approach. Context-specific or context-adapted models are needed to be able of addressing the concrete problems, challenges and needs of real systems and, therefore, to provide proper solutions.

Although it will be explained in detail in chapter 2, state and flow variables along with the close loop relationships among variables constitute the key elements of system dynamic models structure (Shen et al. 2009). System dynamic models (SDMs) provide users with better understanding of system dynamic behaviour by giving insight into the feedback processes. Furthermore, SDMs allow the identification of plausible future scenarios and the major drivers of change and, thus, allow decision makers to anticipate the long-term consequences of their decisions and actions, as well as the unintended consequences of policies and strategies. For Garrity (2011) the complexity of systems means that humans are unable to infer the long-run consequences of their actions without the use of computer simulations. The application of the system dynamics approach have numerous advantages, due to their capacity to conceptualize the complex interrelations and to facilitate their comprehension and monitorization (Martínez-Moyano and Richardson 2013; Kelly et al. 2013) aimed at generating useful information for decision-making (Jakeman and Letcher 2003; Voinov and Shugart 2013).

Many approaches for sustainability have been based on indicators (Bell and Morse 2005; Wiggering et al. 2006; van Zeijl-Rozema et al. 2011). For Singh et al. (2012) and Schneider et al. (2014), indicators provide a reasonably simple tool that allows the analysis and communication of complex ideas by condensing their multifaceted nature into a manageable amount of meaningful information. According to Spilanis et al. (2009), indicators should be useful for users by being simple and capable of illustrating temporal changes and by offering a common ground for comparisons with other areas and critical values or thresholds.

Spangenberg (2002) underlined that, in order to serve as communication tools helping to guide political decision-making towards sustainable development, they should be: i) general (not dependent on a specific situation, culture or society); ii) indicative (representative of the phenomenon they are intended to characterize) and iii) sensitive (reactive to changes in what they are monitoring).

Indicators play a particularly important role in assessing the 'distance-to-target' where quantifiable policy targets have been established (EEA 2012). For numerous authors (Gallopin 1997; Moldan et al. 2012; Proelss and Houghton 2012) the identification of a reference value for sustainability gives the indicator meaning and quantifies what is acceptable regarding sustainability. In this sense, Singh et al. (2012) underlined the increasingly recognition of indicators as a useful tool for policy making and public communication, since they provide decision-makers with an evaluation of integral socio-ecological systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make systems more sustainable.

However, they have also limitations. Gaps in data usually limit the applicability for different study areas. Quantitative indicators often require to (over)simplify complex and dynamic behaviours, hard to measure, which might be neglected (Schneider et al. 2014). Moreover, in socio-ecological systems, the analysis of the interactions between indicators cannot be addressed using traditional, static catalogues of indicators. Sometimes it represents an important constraint in their application and in their influence on the assessment of policies and plans. Therefore, what can sustainability indicators offer to the assessment of policies?

On the other hand, there is a remarkable absence of really integrated tools which are easily accessible to end-users and stakeholders to evaluate concrete questions and that can play a relevant role in the management and decision process of real systems (Granell et al. 2013). Regarding science-policy gaps, Klauer et al. (2013) pointed that one of them lies on the need of dealing with long-term dynamics, since sustainability policies can only be successful if they consider time and, specifically, long time horizons. Long-term planning is especially important when short-term decisions have long-term consequences, since it allows to visualise key issues that may otherwise be missed. For Mahmoud et al. (2009), scenario and policy analysis provides, more than predictions, a dynamic view of the future by exploring various trajectories of change that lead to a broadening range of plausible alternative futures. In this sense, it has a prospective rather than predictive nature.

For Swart et al. (2004) “scenario analysis is an evolving concept” which has been applied to diverse efforts ranging from literary descriptions to model-based projections, from visionary thinking to minor adjustments to ‘‘business-as-usual’’ projections. For these authors, integrated scenarios may be thought of as coherent and plausible stories, told in words and numbers, about the possible co-evolutionary pathways of combined human and environmental systems.

Scenario development, including policy options, is one of the major tools used to visualise and compare the potential outcomes of a variety of policies to meet sustainability objectives, as well as to anticipate the long-term consequences of policy decisions and actions (Zhang et al. 2015). While scenario analysis cannot provide, of course, all the answers to the questions posed, it has an important role to play in thinking about the future, providing insights to policy makers and social agents for better decisions.

However, “if you do not know where you want to go, it does not matter which road you take”. This paraphrase of the Cheshire cat in Alice in Wonderland (Walker et al. 2002) is used to introduce the following questions, applicable to any Biosphere Reserve: Where are the policy decisions of the Reserve driving to? Are we meeting the sustainability aims?

Another fundamental difficulty in managing socio-ecological systems for long-term, sustainable outcomes is the uncertainty (Ascough et al. 2008; Warmink et al. 2010). Since the future is uncertain, Uusitalo et al. (2015) stated that is impossible to predict with certainty the result of each management decision. Therefore, uncertainty should be considered a normal component of decisions. Moreover, the SES great complexity, with many interactions among individual sources of uncertainty, can increase the overall model uncertainty (Perz et al. 2013; Verburg et al. 2013; Ropero et al. 2014). There is a need to identify potential sources of uncertainty and to quantify their impact on the application of certain policies and management options. Nevertheless, the level of testing required to develop this understanding is rarely carried out, largely due to time and other resource constraints (Chu-Agor et al. 2012; Kelly et al. 2013).

In order to assess the management options with confidence, it is essential to explicity address the uncertainty (Ascough et al. 2008; Holzkämper et al. 2015). However, is it possible to consider uncertainty in complex SES models?

1.1.4. Biosphere Reserves as demonstration areas for sustainable development

As a step to move forwards sustainability in real socio-ecological systems, the UNESCO Man and the Biosphere programme established the biosphere reserves in the 1970s (Batisse 1986, 1990), aim at increasing world conservation and facilitating the implementation of international and national planning strategies (Gourmelon et al. 2013). As Price (2002) stated, “over the intervening decades, there have been significant changes in concepts of conservation, in particular the growing realisation that areas of importance for the conservation of biological diversity should no longer be ‘protected’ from those that live around them, but that these people need to play key participatory roles in the management of these areas at the bioregional scale”.

Biosphere Reserves (BRs) provide an example of an integrated sustainability framework that allows for connection between the various dimensions of sustainability. They are also considered as platforms for policies and practices that facilitate conservation and sustainable use of biodiversity, economic growth of local communities, and the emergence of knowledge-based management arrangements at local, national and international levels (Nguyen et al. 2011). The UNESCO (2007) recognises biosphere reserves as “learning laboratories for sustainable development”, where knowledge sharing, research and monitoring, education, training and participatory decision-making are the priorities of the network.

Throughout this work, Biosphere Reserves will be considered as a socio-ecological system (Duffy et al. 2001; González et al. 2008; Matysek 2009). In the face of global change, Biosphere Reserves need to find solutions to management challenges in order to attain the most ecologically sustainable, socially equitable and economically efficient development. This management requires the consideration and integration of all these dimensions, in order to achieve a long-term sustainability (Ariza et al. 2007). Particularly for insular tourist destinations, where policing is extremely challenging, the integration is essential to manage these system, addressing the complexities of interests and perspectives, leading to a more transparent and fair decision-making process (Lozoya et al. 2014).

The case study of this thesis is the Fuerteventura Biosphere Reserve. The reasons behind the selection of an insular Biosphere Reserve is that: i) Insular systems facilitate the assessment of energy and material flows due to their physical boundaries; ii) They are particularly vulnerable regarding natural resources as water and energy and iiii) There is a more tangible sense of limits, which has often promoted an earlier awareness about the need for sustainable development. Furthermore, Fuerteventura is a hype-arid system, with a mean annual rainfall around 100 mm, which conditions the range and type of options for sustainable development on the island. At the same time, Fuerteventura has suffered a quick tourist development and also presents a strong dependence on fossil fuels. All these features make Fuerteventura a relevant case study for the purpose of this thesis.

1.2. OBJECTIVES

The ultimate aim of this thesis is to explore the potential of developing an integrated tool for sustainability assessment which can be useful for the management of real socio-ecological systems, in this case the Fuerteventura Biosphere Reserve. This has been addressed by developing, testing and applying an integral dynamic model in combination with other methods and approaches (indicators, policy and scenario analysis, uncertainty assessment), to provide a tool for prospective analysis and to assist the decision process.

More specifically, the objectives of this thesis, which could give some answers to the questions launched along the Introduction, are:

1. To develop an integral dynamic model of a socio-ecologic system: the Fuerteventura Biosphere Reserve sustainability model (FSM), which includes the key variables and processes in order to understand the dynamics of the system and to test the model by means of model testing procedures. This objective will be addressed in Chapter 3.

2. To integrate a set of indicators proposed by the Action Plan of the Biosphere Reserve and other agents and to analyse the main changes of the SES of Fuerteventura, and the interactions between key variables and indicators. This objective will be addressed in Chapter 3.

3. To apply the FSM to assess how a set of sustainability indicators react under the main environmental measures proposed by different agents, quantify the level of compliance of key environmental aims of the Action Plan, prioritise among these measures by using the indicators and their thresholds, visualise side-effects and trade-offs among environmental objectives and detect not-addressed aims. This objective will be addressed in Chapter 4.

4. To apply an extensive sensitivity analysis (SA) in order to improve model formulation, gain model confidence by performing a detailed assessment of model robustness and identify leverage points as the basis to develop management measures. This objective will be addressed in Chapter 5.

5. To incorporate the uncertainty analysis into the assessment of model outcomes under different policy options and assess how external drivers, such as economic and climate changes scenarios, interact with the uncertainty of model outcomes. This objective will be addressed in Chapter 5.

6. To apply the FSM to perform a detailed analysis of the dynamics of the potential habitat of the houbara bustard (*Chlamydotis undulata fuerteventurae*), to identify the threatening factors which have contributed most to the loss of potential habitat and to assess the expected effects of different future scenarios and policy options on the houbara potential habitat. This objective will be addressed in Chapter 6.

This thesis consists of six chapters. Chapter 2 describes the area of study and the general methodology applied throughout the thesis. Chapter 3 presents the integral dynamic sustainability model, built and tested to understand the dynamics of the Fuerteventura Biosphere Reserve system (the FSM), as well as the main changes along the calibration period (1996-2011). This chapter has been published as Banos-González et al. (2013 and 2015).

The three remaining chapters show different model applications. Chapter 4 uses the FSM model to assess the consistency of the Fuerteventura Biosphere Reserve Action Plan, regarding their sustainability goals, indicators and policy measures. This chapter has been submitted for publishing in Ecological Inidicators (July 2015).

In chapter 5, an extensive sensitivity analysis is performed in order to improve model formulation and its application. Besides a detailed assessment of model robustness, some leverage points were identified, which can be used for management measures development. The uncertainty analysis is also incorporated in the assessment of model outcomes under different policy options and scenarios.

Chapter 6 represents another application of the FSM, showing the use of the model to carry out an extensive analysis of specific sectors of processes, in this case, to understand the changes in the houbara potential habitat, linking the main threatening factors for the habitat to the general dynamics of Fuerteventura. This chapter has been submitted for publishing in European Journal of Wildlife Research (July 2015).

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CHAPTER 2

Methodology

2. METHODOLOGY

2.1. AREA OF STUDY

Fuerteventura (28º 27' N, 14º 37' O) (**Fig. 2.1**), is the second largest island of the Canaries archipelago, about 1,650 km^2, and the closest one to the continental margin of Africa (115 km to the nearest point). Due to the long lasting erosion processes, Fuerteventura has a smooth relief, only interrupted by the massif of the peninsula of Jandía with the Pico de la Zarza (807 m) and the massif of Betancuria (724 m) (Brandes and Fritzsch 2000).

Figure 2.1. Area of study: Fuerteventura (Canary Islands, Spain) and its municipalities.

It has a desertic hyperarid infra-thermomediterranean climate (Torres Cabrera 1995), with a yearly precipitation of less than 200 mm/year in the relative high elevation, while at low altitudes precipitation it does not exceed 60 mm/year. Between 1996 and 2011, an average annual precipitation of 99 mm/year was recorded, with less than 35 mm in 2009 (Tiempo 2014). The island orientation, emplaced near the Saharan belt, and the aforementioned relatively low topographic elevations do not favour the condensation of the wet trade winds (Lloret and González-Mancebo 2011; Herrera and Custodio 2014).

Fuerteventura combines: (a) relatively high environmental homogeneity in terms of topography, climate, soil or vegetation across the island, but with geographical areas differentially threatened by urban sprawl (depending on tourist attractiviness); and (b) a broad spectrum of ecological characteristics, ranging from extremely common species present throughout the Western Palaearctic, to local endemics only present on this island (Carrascal et al. 2012).

These peculiarities clearly mark the biodiversity of Fuerteventura, with around 5% of endemism (Izquierdo et al. 2004; Arechevaleta et al. 2010), such as *Euphorbietum handiensis*, *Kleinio neriifoliae-Asparagetum pastoriani* and *Aichryson bethencourtianum* regarding flora endemism and *Saxicola dacotiae* among faunal endemism.

The vegetation is dominated by substitution vegetation as xerophytic scrubs (*Launaea arborescens*, *Lycium intricatum*, *Salsola vermiculata*, *Suaeda* spp. and *Euphorbia* spp.) and annual grasslands frequently degraded due to goats overgrazing (Rodríguez-Rodríguez et al. 2005; Schuster et al. 2012), since traditional grazing systems (mainly goats and sheeps, **Fig. 2.2a**) are partially maintained in some inner areas of the island (Gangoso et al. 2006).

The small patches of native vegetation are relegated to inaccessible or unfavourable areas. The main potential vegetation is *Euphorbia balsamifera* scrub, restricted to isolated sites of difficult access such as ravines and steep slopes (del Arco et al. 2010).

The degree of threat posed by this biodiversity is severe, with 28 species and subspecies showing some category of threat (Martin et al. 2005): 9 endangered, 3 sensitive to habitat disturbance, 14 vulnerable, and 2 which are already considered extinguished. This is 15 plant species, 11 vertebrates and 2 invertebrates among these categories of threat.

Among these species, the Action Plan of the Biosphere Reserve highlights two endangered species included in the National Catalogue of Threatened Species (BirdLife 2004; Lorenzo 2004) and endemic subspecies of The Canary Islands: the Canarian Houbara Bustard (*Chlamydotis undulada fuerteventurae*) and the Egyptian vulture (*Neophron percnopterus majorensis,* **Fig. 2.2b**). This work focused on these two flagship species for the development of the biodiversity sector in the Fuerteventura Sustainability Model.

Figure 2.2. a) Goats grazing b) Egyptian vulture (*Neophron percnopterus majorensis*).

The contribution of Fuerteventura island to the Natura 2000 Network may be summarised as follows (**Fig. 2.3**): 13 Site of Community Importance (48,328 ha) and 9 natural area classified as Special Protection Area (68,713 ha). Furthermore, the saltmarch “Saladar de Jandía” is included in the Ramsar List of Wetlands of International Importance.

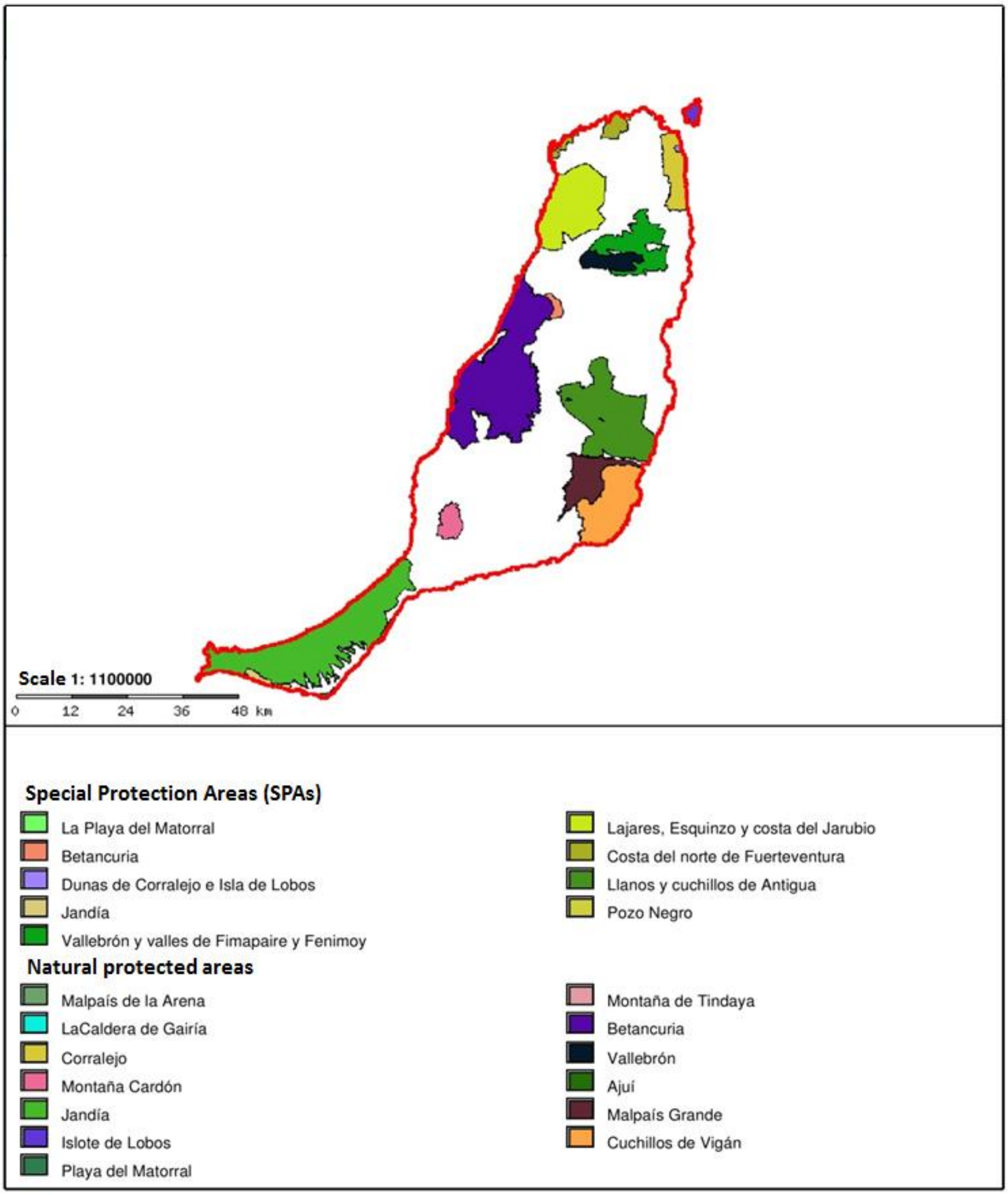

Figure 2.3. Protected areas included in the Natura 2000 network and conservation zones in the Biosphere Reserve of Fuerteventura.

A distinguishing feature of Fuerteventura landscape is the existence of dune systems formed by “jables” (land with wind origins), which constitute the habitat for singular animals and plants (**Fig. 2.4a**). The interior plains (**Fig. 2.4b**) constitute another geomorphologic characteristic element of Fuerteventura, where lots of structures linked with scarce water resources use could be found.

Figure 2.4. a) Corralejo Dunes. b) Landscape between Betancuria and Antigua.

In Fuerteventura there is no permanent surface water and the *barrancos* flow only after intense rainfall events and for a very short time (Herrera and Custodio 2000). In the old times, some large cisterns (*maretas*) collected runoff from slopes, for town supply. Now, most potable water is desalinated ground and sea water. Intense rain events produce some local diffuse and concentrated recharge of shallow aquifers. They were mostly fitted with windmills. There are a few brackish water springs (*nacientes*) which reduce almost to seepages producing no more than a few litres per day.

In the extremely arid climate, agriculture has been sustained for decades by a traditional runoff-capture farming system known as “gavias” (**Fig. 2.5a**), which constitute cultural landscapes adapted to the aridity and based on the water and land conservative management (Díaz et al. 2011). Traditionally, gavias were cultivated to grow mainly cereals (*Triticum aestivum, Hordeum vulgare, Avena sativa, Zea mays*) and legumes (*Lens esculenta, Cicer arietinum, Phaseolus lunatus, Medicago sativa*) without addition of chemical or organic fertilizers due to their capacity for washing salts from the soil, moisturizing and fertilizing it with nutrients carried in water runoff (Tejedor et al. 2002; Hernández-Moreno et al. 2007; Díaz et al. 2011). In order to maintain these environmental functions, the insular government (the Cabildo) promoted the implementation of an Abandoned Gavias Restoration Plan (**Fig. 2.5b**).

Figure 2.5. a) Active gavias. b) Abandoned Gavias Restoration Plan, by the Cabildo of Fuerteventura.

Small urban areas and farmers depend on groundwater for human supply, irrigation of small orchards and cattle raising. The high salinity of groundwater in Fuerteventura island is due to intense evaporation of rainfall, which incorporates marine airbone salts in an arid environment (Herrera and Custodio 2000). The limited role of groundwater in the island water planning is also shown by the scarce new data in the available Fuerteventura Water Plan documents (CIAFV 2009). Since well water is brackish, it is often treated by reverse osmosis to reduce salinity and the produced brines are conducted to the coast through a duct network.

Water supply to towns and tourist areas is currently done by large seawater desalination plants. Few efforts have been made until this moment to reduce the dependence of external and non renewable energy resources on the island, which represents a clear sign of unsustainability. While the desalination capacity currently set up on the island is estimated around 27.57 Hm^3/year, following the Fuerteventura Water Consortium (HPF 2013), only around 1.46 Hm^3/year is produced by a wind farm for self- consumption associated with a sea water desalination plant in Corralejo (Renforus 2014). This example illustrates the lack of prominence of renewable energy on the island. The rising dependence on external, non-renewable energy resources might be interpreted as one of the main threatens to the Fuerteventura sustainability, and should represent one of the major challenges for policy intervention.

On the other hand, Fuerteventura is known for its beaches, which are the largest of the seven Canary Islands, and which can be found all over the coast, especially attractive for surfing and other aquatic activities (Santana-Jiménez and Hernández 2011).

Since the beginning of the 90s, the accommodation facilities in Fuerteventura has grown rapidly in both hotel and non-hotel accommodation, with very little weight of the rural tourism (**Fig. 2.6**). Tourists are concentrated mostly along the coast of the Pájara and La Oliva municipalities. This quick and disorganized growth has made the island a destination for mass tourism, affecting the image of the wild and peaceful island, which was its distinguishing feature compared to other coastal destinations with similar climatic conditions.

The number of arrivals has showed a growth rate of 374% from 1990 to 2010, when the island received almost a million and a half of foreign tourists (Government of the Canary Islands 2010a), turning tourism into the most relevant sector in the economy nowadays. As a consequence of the industry development, the island has experienced the greatest economic improvement of the archipelago in the last decade until 2008, when it stopped due to the international economic recession. Tourism in Fuerteventura is highly dependent on tourism marketing through tour operators, which results in a low average spending per tourist at destination, around 25% in average between 2006 and 2010 (Government of the Canary Islands 2010b).

Moreover, Fuerteventura has experienced a spectacular population growth, with a rate of 282% from 1990 to 2010, and more than a hundred thousand of inhabitants in 2010 (ISTAC 2010). Nevertheless, Fuerteventura is still the island with the lowest population density (40 inhabitants/km^2 in average between 1991 and 2010, ISTAC 2010).

In the last decades, tourist development and the population growth have triggered land uses changes, especially intensive in some coastal areas. Traditional productive activities (ranching, artisanal fishing and non irrigated land farming in gavias) have been mainly substituted by tourism and related activities. The abandonment of traditional agricultural lands has prompted the degradation of rural landscapes and the acceleration of processes of soil erosion.

Figure 2.6. Hotel and non-hotel accommodation from 2000 and 2012 (Source: Government of the Canary Islands 2010c).

Therefore, tourism represents the main driving force of the socioeconomic and environmental changes on the island, especially fragile due to the insularity and extreme aridity (Fernández-Palacios and Whittaker 2008; Santana-Jiménez and Hernández 2011), leading to the emergence of new socio-ecologic requirements.

The island of Fuerteventura was declared Biosphere Reserve (BR) by UNESCO in 2009 (BOE 2010). It has an area of 353,500.6 ha, of which 165,664 ha (46.86%) correspond to terrestrial and 187,836 ha (53.14%) to the marine area. The boundaries of the BR are determined by the terrestrial boundaries of the Island, surrounded by a marine strip of 5 miles on Western sector and 3 miles on the rest of the outline (**Fig. 2.7**). As mandated by UNESCO (1984), the biosphere reserve structure divides protected areas into different zones with varying management regimes: i) the core zones require strict protection while multiple use zones permit ‘traditional’ livelihood activities deemed compatible with conservation goals, which in Fuerteventura covers around 69,213 ha; ii) the transition area (Ishwaran et al. 2008), which has have fuzzy boundaries in conformity with the open-ended nature of the process of stakeholder cooperation deemed to be an essential feature of biosphere reserves (UNESCO 1984); iii) the buffer zone (Price 2002), encircles populated areas and according to the structure, sustainable development and appropriate resource management projects should be provided to encourage support for conservation (Sundberg 2003).

The Action Plan of the Fuerteventura Biosphere Reserve (AP) represents a guide to achieve a series of sustainability goals (Action Plan 2013) and constitutes one of the basis for this work.

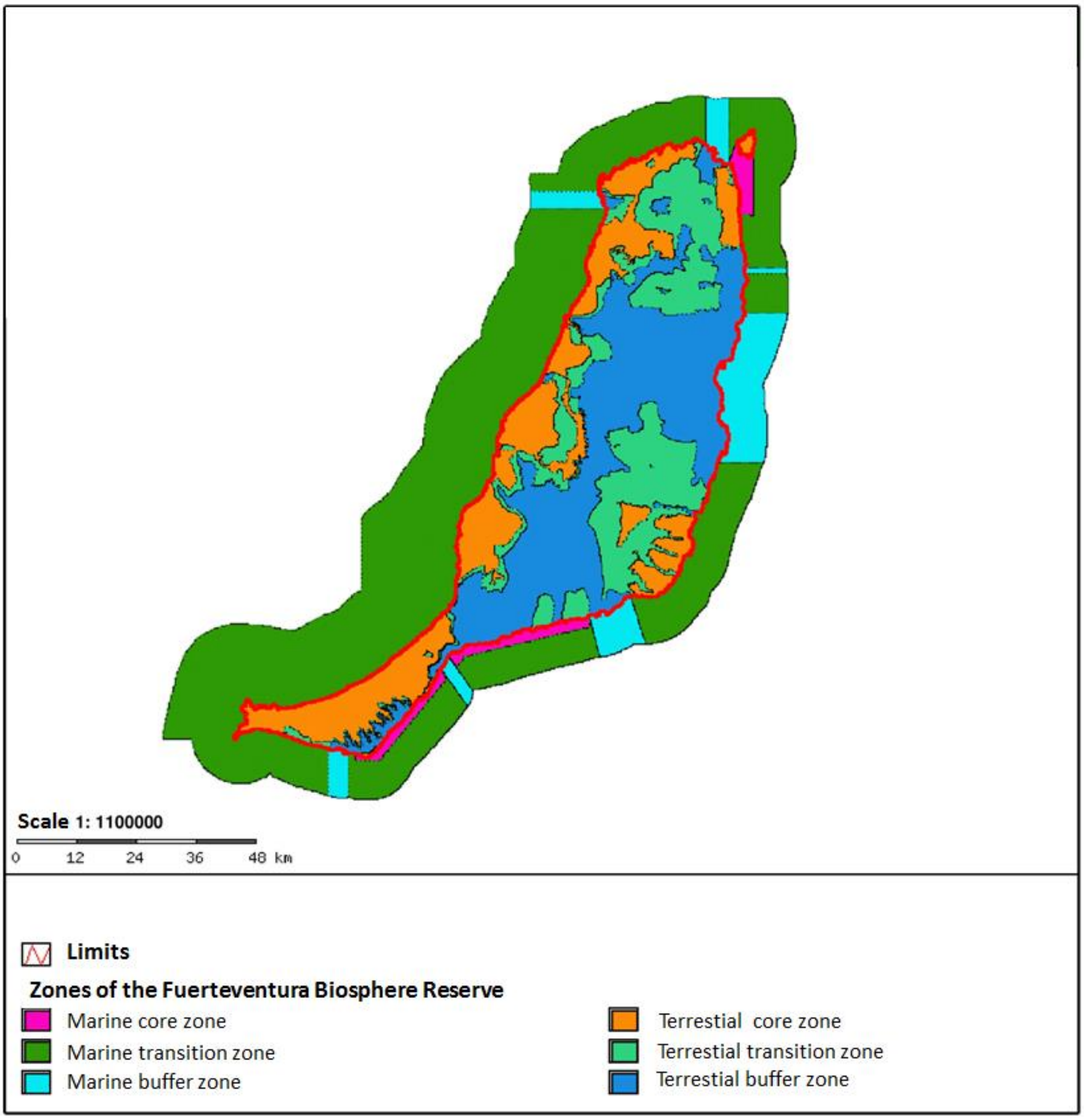

Figure 2.7. The different zones of the Fuerteventura Biosphere Reserve.

2.2. SYSTEM DYNAMIC MODELLING

2.2.1. Overview

System dynamic models (Forrester 1961, 1994; Meadows et al. 1972; Ford 1999; Sterman 2000; Martínez-Moyano and Richardson 2013) is one of the methods that facilitate the recognition of interactions among interconnected subsystems driving the behaviour of dynamic systems (Mirchi et al. 2012), by means of the causal relationships, feedback loops, delays and other processes (Kampmann and Oliva 2008; Li et al. 2012). As Kelly et al. (2013) pointed out, system dynamic models (SDMs) useful learning tools that help improve system understanding and knowledge integration for modellers and end users.

Some of the main features of system dynamics could be summarised as follows:

- The system dynamics approach helps us to better understand the dynamic relations in the system and become aware of their changes through a learning process (Hjorth and Bagheri 2006).

- SDMs are aimed to explain “behavior as endogenous consequences of the feedback structure” (Sterman 2000).

- SDMs are focused on the integral behavior of the system, since the model was built as a whole (Voinov and Shugart 2013). For these authors, stakeholder involvement are essential to improve the communication between disciplines and to ensure that model complexity is kept under control and that new emergent properties are recognized in the integral model.

- SDMs reveal the weakness in our knowledge and can therefore be used to set up research priorities (Jørgensen and Fath 2011).

- SDMs apply a problem-specific approach. The context-specific nature of problems in socio-ecological systems naturally demands context-specific models and tools. As it has been pointed out (Galic et al. 2012), model outputs cannot be easily transferred between contexts without a reconsideration of model assumptions, structure, parameterization and intended purpose.

- Their application is oriented to the generation of problem solutions, using these models for policy testing, what-if scenarios or policy optimization (Oliva 2003). Moreover, for Han et al. (2009), the expected system changes under different “what-if” scenarios is pretty useful in examining and recommending policy decisions.

Qin et al. (2011) summarized the advantages of using a SDMs as follows: a) It can address problem at different scales and support a variety of application goals; b) It has the capacity to describe the feedback relations among sub-systems, as well as the relations between the system and the external environments; and c) It can be quickly understood by different users and facilitate public participation due to its transparency and easy information exchange among sub-systems.

Moreover, system dynamics models have been revealed very useful in the study of a wide number of SES (Martínez-Fernández and Esteve-Selma 2004; Shen et a. 2009; Sandker et al. 2010; Tomlinson et al. 2011; Marín et al. 2012; Pérez et al. 2012; Martínez-Fernández et al. 2013) and, specifically, to facilitate the seek of an integrated management on insular SES (Chang et al. 2008; González et al. 2008; Jørgensen 2013); the sustainability assessment of tourism destinations (Lacitignola et al. 2007; Patterson et al. 2008; Xing and Dangerfield 2011) and Biosphere Reserves (Duffy et al. 2001; Patterson et al. 2004; van Mai and Maani 2010; Rouan et al. 2010; Nguyen et al. 2011); as well as to monitor sustainability indicators (Jin et al. 2009; Feng et al. 2012; Vidal-Legaz et al. 2013; Liu et al. 2014).

On contrast, several shortcomings of system dynamics have been pointed out. Mirchi et al. (2012) highlighted that one of the main limitations of the SD tools lies on the requirement of substantial interdisciplinary knowledge to generate meaningful quantitative predictions due to the complexity and multitude of subsystems and interactions. Another limitation lies on the fact that neither data nor parameter uncertainty are explicitly considered in the model structure and therefore it requires a comprehensive testing of the model to allow this understanding to be developed. These procedures are frequently missing due to time and other resource constraints. Moreover, the treatment of space is also very limited in this type of model building tools, although this is not due to a limitation in the method but rather the nature of these tools (Kelly et al. 2013).

2.2.2. Basic methodologial elements

According to Jørgensen and Fath (2011), in its mathematical formulation, a model has mathematical equations, forcing inputs (external variables), state variables (major accumulations or depletions over time), flow variables (rate of change in state variables) and parameters (constants).

The state variables are referred to the integral concept, in mathematical terms (**Eq. 2.1**).

$$N(t) = N(0) + \int_0^t (FE - FS)dt \tag{2.1}$$

Where *N* is the state variable; *t* is the considered time period, *N(0)* is the initial value of the state variable at t_0; *FE* is the input rate and *FS* is referred to the output rate.

Usually there are also auxiliary variables, which are intermediate variables used to compute the flows, that help to formulate and calibrate the model. In the stock and flow diagrams the connections between these elements are represented by arrows (**Fig. 2.8**).

Feedback loops are essential in system dynamic models (Saysel 2007; Liu et al 2012; Kampmann and Oliva 2008). There are two types of feedback loops in systems: positive loops and negative loops (Forrester 1975; Yim et al. 2004; Sterman 2000; Martínez-Moyano and Richardson 2013). In positive loops, a change (positive or negative) in one variable results in changes of the same sign on other variables, which in turn lead to also a change of the same sign in the first variable. Then, a positive feedback loop generates a reinforcing behaviour, that is, exponential growth or decay. In negative loops, a change in one variable results in changes in other variables which in turn lead to a change of opposite sign in the first variable. Thus, a negative feedback loop generates a balancing behaviour, that is, an equilibrating behaviour around a goal. Interactions of positive and negative loops generate complex system behaviours of exponencial growth, collapse, oscillations, logistic growth and others (Bérard 2010; Kampmann and Oliva 2008; Vugteveen et al. 2015).

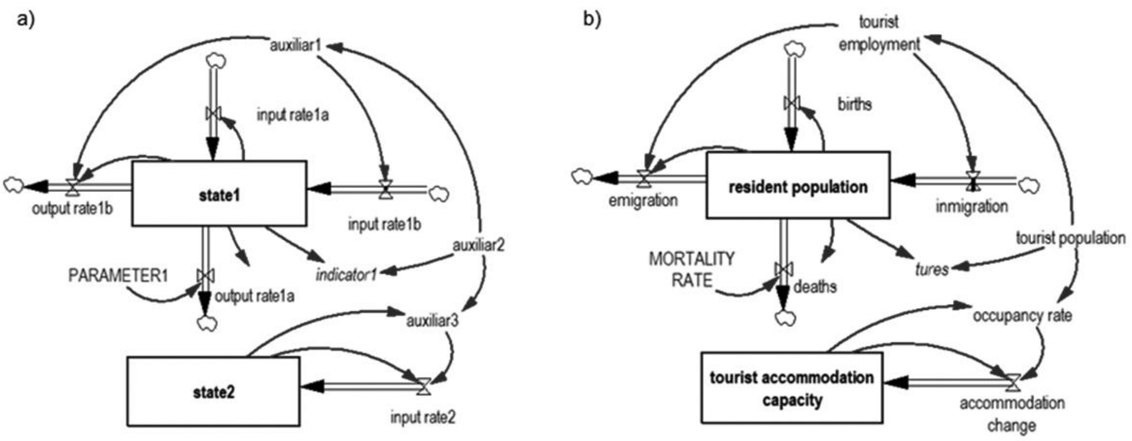

Figure 2.8. Stock and flow diagram: a) General diagram where the main types of variables are represented (rectangles symbolise the state variables; thick arrows represent input and output rates; blue arrows connect auxiliary variables; variables in italics represent indicators). b) The same diagram, applied to the FSM.

Several feedbacks can be found in the FSM. **Figure 2.9** shows an example in which the occupancy rate and the tourist accommodation capacity are involved: the construction of new tourist accommodations triggers the tourist arrival and, therefore, the increase in occupancy rate. This leads hoteliers to build new tourist accommodations (positive loop). At the same time, as the offer of accommodation increases, the occupancy rate tends to decrease and it may slow down the new hotels construction (negative loop).

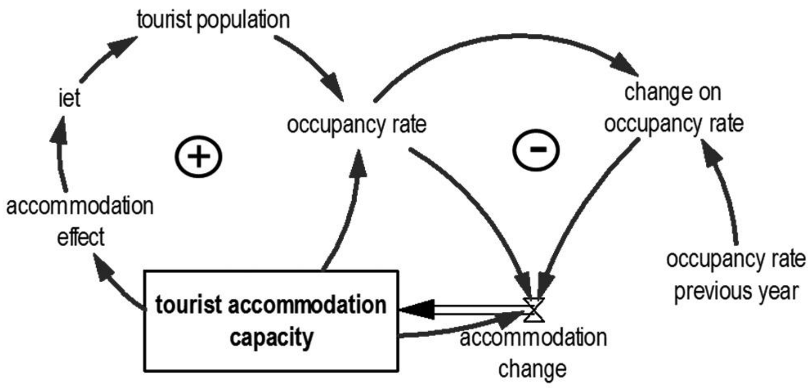

Figure 2.9. Positive and negative feedback loop.

2.2.3. Modelling stages

The modelling process involved several stages (**Fig. 2.10**): conceptualisation, formulation of model equations, model testing and calibration.

An iterative approach is applied in which the cycle conceptualization-formulation-preliminary testing and calibration is followed several times throughout the model building process.

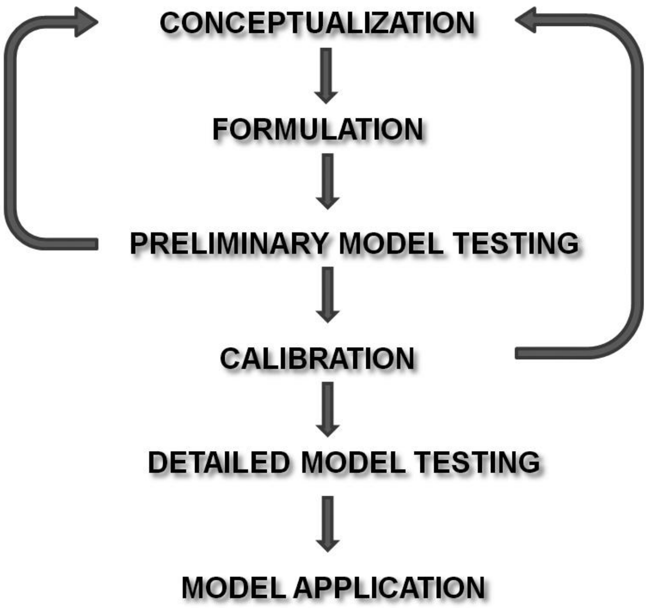

Figure 2.10. Stages of the modelling process.

Conceptualization.

The first step on model building consists on defining the problem and the main goals of the model. In the case of the FSM, the model was intended to describe the main socio-economic and environmentals components of the Fuerteventura Biosphere Reserve along with the key environmental problems and processes. The determination of the spatial, temporal and conceptual limits of the system is also carried out in this stage. The conceptual limits refer to the identification of the endogenous variables, whose dynamic behaviour depends on other model variables. The identification of parameters and forcing inputs, constituting the boundary conditions of the model, is also required.

This conceptualization phase may include a diagram of the conceptual model (**Fig. 2.11**) or even start with the elaboration of a stock and flow diagram. It represents a qualitative description of the main factors and interrelations, and shows the initial hypothesis regarding the dynamic behavior of the system. In this work, besides this conceptual diagram, a matrix of the main strengths, weaknesses, opportunities and threats (SWOT) was developed (**Table 4.1**), which allowed to identify and define the main strengths, weakness, opportunities and threatens of the system.

Formulation

This stage includes the mathematical formulation of the variables and flows according to the conceptual model, as well as the determination of parameters and initial conditions.

Model building and analysis is often done using a 'nested' partial model testing approach (Kampmann Oliva 2008; Saleh et al. 2010), where one goes from the level of small pieces of structure to entire subsystems of the model, with frequent re-use of known formulations and partial models. Often, writing equations reveals gaps and inconsistencies that must be remedied in the prior description.

The mathematical formulation of the FSM can be found in Annex I.

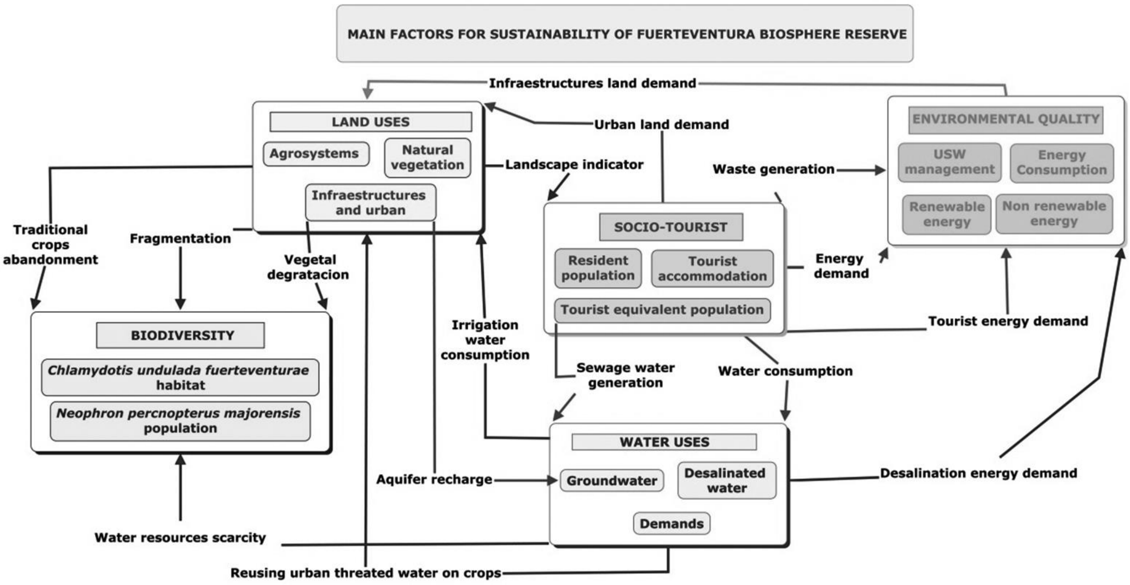

Figure 2.11. Conceptual model for the Fuerteventura socio-ecological system.

Calibration

Model calibration is the process of estimating the model parameters for a close match between observed and simulated behaviour (Oliva 2003; Muleta and Nicklow 2005). Calibration explicitly attempts to link structure to behaviour. Confidence that a particular structure, with realistic parameter values (Ford 1990; Makler-Pick et al. 2011) is a valid representation increases if the structure is capable of generating the observed behaviour. Some parameters can be found in the literature, not necessarily as constants but as approximate values or intervals (Jørgensen and Bendoricchio 2001). Parameters can also be provided by empirical studies, field data, technical documents and statistical servers.

In the development of the FSM, when no reliable information was available from the aforementioned sources, an automatic calibration process was carried out (Oliva 2003), which allows to select the parameter values that maximize the simulation pay off, using the Powell hill climbing algorithm (Vidal-Legaz et al. 2013). During this process, it is important that the parameter ranges are constrained to realistic values for the target system, since it increases the power of the calibration without compromising the resulting model structure (Holmes and Johnstone 2010).

Model testing

By means of a set of testing procedures, the model is improved and model confidence is built. This confidence is based in both the structure and the capacity to track the known behaviour about the system under investigation (Homer 2012). Moreover, detailed model testing in complex socio-ecological system models is an ongoing process, and must be applied to every stage of modelling (Xing and Dangerfield 2011).

Typical questions in this phase are: Does the model react as expected? Is the model stable in the long term? Is the use of units consistent? Does the model react as expected?. In order to answer these questions, a set of model testing procedures was applied to the FSM, including the following (Barlas 1996):

Model simulation beyond temporal limits: The model simulations were expanded to 2100 (**Fig. 2.12**), enough long period to detect any anomalous behaviour in the long term, and to test the coherence of the dynamic model (Jørgensen and Fath 2011).

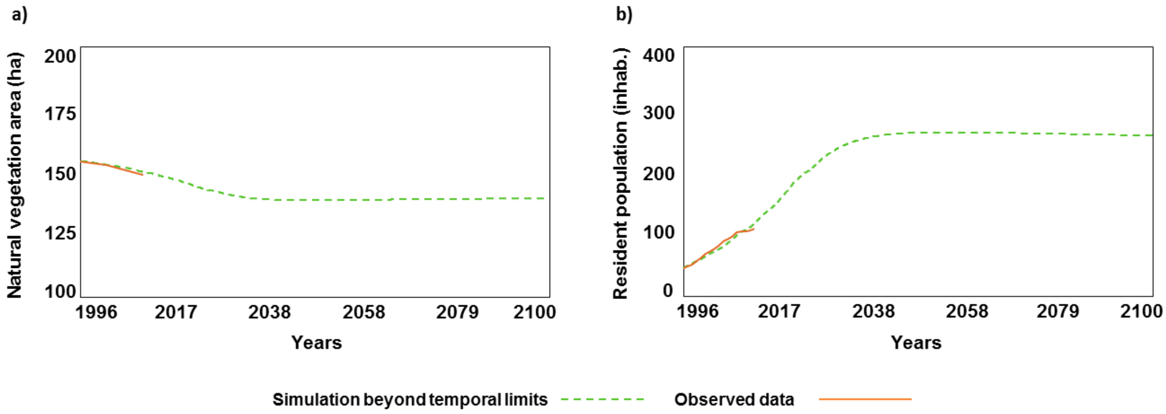

Figure 2.12. Examples of the model simulation beyond temporal limits.

Dimensional consistence test: According to Barlas (1996) it is classified as a theoretical test in the sense that it is an internal consistency test. This test checks whether the dimensions of variables in the model correspond to the unit in which they can meaningfully express the real variables. This is carried out by checking the right-hand side and left-hand side of each equation for dimensional consistency. The test was conducted using built-in functions of the software use for system dynamics model development.

Extreme condition test: It involves evaluating the validity of model equations under extreme conditions, by assessing the plausibility of the resulting values against the knowledge of what would happen under a similar condition in real life. The expressions used for this test could be as:

IF (extreme condition) → (expected result)

In this work, a set of extreme conditions tests was performed using an automated procedure with the Reality Check function of Vensim software (Ventana Systems 2011), which has proven useful for testing socio-ecological dynamic models (Vidal-Legaz 2011; Li et al. 2012). Some examples can be found in Chapter 3 and in Annex II.

Sensitivity analysis (SA): This analysis allows an assessment of the model robustness by analysing the uncertainty in model outputs in the response to changes in the concerned parameters (Schouten et al. 2014).

Comparison with observed data: Analysis of the historical fit of the model is a part of the behaviour reproduction test, but this test is more than comparing the correspondence of simulated and actual data on a point-by-point basis. The test usually focuses on the character of the simulated data, to see whether it exhibits the same modes, phase relationships, relative amplitudes, and variability as the real data (Stermanm 1984).

For Rykiel (1996), this process is a pragmatic approach to validation because it is concerned primarily with how well the model mimics the system regardless of the mechanisms built into the model. Statistical tests of comparisons between simulated and real data are widely used to evaluate model behaviour. Bert et al. (2011) stated that the focus of the model testing is to ensure that the fundamental structural and behavioural components in the model capture the main aspects of the actual system.

Despite the fact that all quantitative models are imperfect (Graham et al. 2002) and that one model could rarely be the best always for any given set of data (Goh and Low 2002), the accuracy of the model needs to be evaluated. In this sense, Oliva (2003) claimed that there are multiple measures of fit of simulation output to observed data, and the selection of a measure should be based on the purpose of error analysis (Sterman 1984; Reichelt et al. 1996; Kleijnen and Sargent 2000). Among a number of possible criteria, the most commonly used are: the Theil's inequality statistics, the mean-squared error (MSE), the mean absolute percentage error (MAPE), the root-mean-squared error (RMSE), and the normalised root-mean-squared error (NRMSE).

The Theil's inequality statistics (Theil 1966) decompose the MSE (**Eq. 2.2**) between simulated and actual series into three components: bias (U^M), unequal variation (U^S), and unequal covariation (U^C), **equations 2.3, 2.4** and **2.5**, respectively. Dividing each component by the MSE gives the fraction of the error that is due to unequal means, unequal variances, or imperfect correlation. For a full description of how to interpret these statistics for goodness of fit of systems dynamics models and the identification of systematic errors, see Sterman (1984).

$$MSE = \frac{1}{n}\sum_{t=1}^{n}(S_t - A_t)^2 \qquad \textbf{(2.2)}$$

$$U^M = (\bar{S} - \bar{A})^2 / MSE \qquad \textbf{(2.3)}$$

$$U^S = (S_S - A_A)^2 / MSE \qquad \textbf{(2.4)}$$

$$U^C = 2 \cdot (1 - r) \cdot S_S \cdot S_A / MSE \qquad \textbf{(2.5)}$$

where $\bar{S}$ and $\bar{A}$ are the simulated and observed average value, respectively; S_S and S_A represent their standard deviation; *r* means the correlation between simulated and observed data; *n* is the number of observations and S_t and A_t the simulated and observed value at time *t*, respectively.

The mean absolute percentage error (MAPE, **Eq. 2.6**) is a measure of accuracy of a method for constructing fitted time series values in statistics, specifically in trend estimation. It usually expresses accuracy as a percentage. Goh and Low (2002), following the guidelines to classification of MAPE defined by Lewis (1982), evaluated the simulation results with errors of less than 10% as "highly accurate," those between 10% and 20% are considered "good," those between 20% and 50% are considered "reasonable," and those with errors greater than 50% are considered "inaccurate."

The RMSE, the square root of MSE, and the normalised RMSE (NRMSE, **Eq. 2.7**) quantify the typical size of the error in the simulations. According to Andarizan et al. (2011) and Sepaskhah et al. (2013), NRMSE gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent when a normalised RMSE is less than 10%, good if the normalised RMSE is greater than 10% and less than 20%, fair if NRMSE is greater than 20 and less than 30%, and poor if the normalised RMSE is greater than 30%

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{S_t - A_t}{A_t}\right| \qquad \textbf{(2.6)}$$

$$NRMSE = \frac{1}{\bar{A}}\sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(S_t - A_t\right)^2} \qquad \textbf{(2.7)}$$

where $\bar{A}$ is the observed average value, n is the number of observations and S_t and A_t the simulated and observed value at time t, respectively.

2.2.4. Model application

In management and decision processes, diverse alternatives need to be tested for decision-making. System dynamics models are generally built to assess the effectiveness of alternative policies or to design strategies for improving the behaviour of a given system under external changes or scenarios (Barlas 1996).

The alternatives may come from intuitive insights generated during the first stages, from experience of the analyst, from proposal advanced by stakeholders, or from an exhaustive policy and scenario analysis (Saleh et al. 2010).

In this thesis, the FSM has been applied to assess the consistency among the main environmental objectives, sustainability indicators and environmental policies of the Fuerteventura Reserve Action Plan (Chapter 4), to identify the leverage points of the system and analyse the effects of uncertainty on the assessment of policies and scenarios (Chapter 5) and to show one example of model application for an in-depth understanding of specific sectors of processess, in this case, the houbara habitat (Chapter 6).

In order to simulate each policy measure, the model structure was expanded to include all necessary new variables, parameters and relationships. This required to perform an additional stage of model building, from data gathering to model formulation. The final model version is therefore ready to simulate all considered policy options and scenarios.

2.3. INTEGRATION OF SUSTAINABILITY INDICATORS

To help make society more sustainable, tools that can both measure and facilitate progress towards a broad range of social, ecological and economic goals are claimed (Reed et al. 2006). One of the biggest challenges is to reduce the complexity of the observed processes and the collected information, and to develop an assessment framework able to offer an empirical test as to whether a certain state of the system is sustainable or not (Lotze-Campen 2008; Poveda and Lipsett 2014). As such, the selection and interpretation of sustainability indicators has become an integral part of international and national policy in recent years. They are considered an essential component of sustainability assessment, since they provide a reasonably simple tool that allows the analysis and communication of complex ideas into a manageable amount of meaningful information (Singh et al. 2012; Schneider et al. 2014). Indicators are popular for establishing league tables (Moldan et al. 2012). However, the static ranking or catalogues alone does not say much about sustainability. Moreover, it is increasingly claimed that indicators just have a moderate weight on the adoption and assessment of sustainable policies and practices (Reed et al. 2006; Levrel et al. 2009; Kajikawa et al. 2011).

Two reasons may explain this fact. On one side, indicators should be applied over a period of time, showing the continuous changes in the processes they represent (Reed et al. 2006). On the other side, absolute values may not entirely matter; thus, a notion of what is acceptable is needed. Lancker and Nijkamp (2000) emphasized that “a given indicator does not say anything about sustainability, unless a reference value such as thresholds is given to it”.

In order to overcome these limitations, we propose a set of methodological improvements, which have been implemented along this work (see Chapter 3, 4 and 5 for their application).

First, a limited and manageable number of indicators creates a more useful tool than a large number of unselected ones (Lancker and Nijkamp 2000). A careful selection was carried out to define the indicators finally included into the model. Furthermore, the process of definition and selection should involve local agents and stakeholders. In this work, the selection of the sustainability indicators was done based on the Action Plan and other regional catalogues (Cáceres 2010; Action Plan 2013) and taking into account the most relevant themes for sustainability identified with the participation of an experts panel (see Chapter 3).

Secondly, as stated by Moldan et al. (2012), indicators should show the ongoing changes in the processes they represent. Moreover, they should be able of resembling the interactions along the system, which dynamically occur over time (Guo et al. 2001; Guan et al. 2011). For this purpose, the selected sustainable indicators were integrated into a system dynamic model to visualize their change along time and to assess how any variation on one indicator may lead to a series of responses on other indicators.

In terms of interpretation of the indicators and in order to represent a useful tool for public communication and for the assessment of policy and management options, a quantitative notion of what is acceptable for sustainability is needed (Lancker and Nijkamp 2000; Moldan et al. 2012). Setting sustainability objectives and identifying appropriate indicators with their thresholds to monitor progress towards these targets over time may increase their influence on the adoption and assessment of sustainable policies and practices. In this thesis an effort has been applied to identify specific quantitative thresholds for the sustainability indicators included in the model. In this way, the impact of different measures and scenarios on the sustainability of the Fuerteventura Biosphere Reserve can be more precisely assessed comparing the behaviour of the indicators in relation to their respective thresholds.

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CHAPTER 3

Dynamic integration of sustainability indicators in insular socio-ecological systems

3. DYNAMIC INTEGRATION OF SUSTAINABILITY INDICATORS IN INSULAR SOCIO-ECOLOGICAL SYSTEMS*

Abstract

The sustainability assessment on socio-ecological systems requires a systemic perspective in order to address the close relationships between the environmental and socio-economic processes. This need is especially urgent in the case of arid insular systems where limiting factors, as land and water resources, are more evident. The hyperarid island of Fuerteventura (The Canary Islands, Spain) represents a challenging case due to the need for compatibilising the rising tourist development with the sustainable management of its natural resources, highly vulnerable due to processes such as the degradation of natural habitats -which hosts endemic and endangered species- or the high dependence of allocthonous energy sources for basic processes, including water supply.

In this work an integral dynamic model is presented, the Fuerteventura Biosphere Reserve sustainability model (FSM), tested and calibrated for 1996-2011 period. The FSM allows to understand the main components of this socio-ecological system and their changes along time, as well as the interaction between the included sustainability indicators and other factors within the system. Results have shown the existence of potential trade-offs not only between socioeconomic development and conservation options, but also between sustainability goals under different management options. The conservation of the Houbara habitat might require the elimination of traditional agro-systems restoration plans, although these agro-systems offer important environmental functions. Besides, a reduction of cattle herd in order to control the degradation of high quality vegetation might negatively affect the endangered population of scavengers on the island. The water-energy binomial offers another trade-off regarding sustainable development, due to the strong dependency of the water availability on energy consumption. In this sense, the FSM has shown to be a useful tool to improve the comprehensive diagnosis of the system and to identify trade-offs between sustainability indicators to orientate management policies for this insular socio-ecological system.

Key words: indicators dynamic integration; insular systems; integral models; socio-ecological systems; sustainability.

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Banos-González I, Martínez-Fernández J, Esteve-Selma MA. (2015). Dynamic integration of sustainability indicators in insular socio-ecological systems. Ecological Modelling, 306, 130-144. DOI: 10.1016/j.ecolmodel.2014.08.014

3.1. INTRODUCTION

The analysis of a socio-ecological system (SES) should be tackled from a holistic, systemic perspective that enables an integrated assessment of socioeconomic and ecological factors and the linear and nonlinear interactions and feedbacks, which characterize complex socio-ecological systems (Lacitignola et al. 2007; Halliday and Glaser 2011).

The application of this systemic perspective for sustainability assessment on insular socio-ecological systems has an increasing interest (Patterson et al. 2004; Aretano et al. 2013), due to its large potential as observatories of sustainability, where the narrow interaction between ecological aspects and socioeconomic processes is explicitly acknowledged. Regarding sustainability analysis and modelling, two advantages have been identified in the case of insular systems (Jørgensen 2013; Petrosillo et al. 2013): i) an easier identification of flows, facilitating the quantification of sectors and variables and ii) insular systems allow to visualize the existence of physical limits and carrying capacity and this facilitates the establishment of sustainability thresholds

Indicators are an essential component of sustainability assessment. Despite of this potential, sustainable indicators have had a moderate influence on the adoption and assessment of sustainable policies and practices (Hukkinen 2003; Levrel et al. 2009; Kajikawa et al. 2011). Among other reasons, the use of static catalogues of indicators, which do not consider the dynamic interrelations between the relevant processes, represents one of the most important limitations in their application.

In order to overcome some of these limitations, this work suggests the use of system dynamics modelling tools, since they provide a framework for the development of sustainability models, thanks to their capacity to conceptualize the complex interrelations of these SES (Bérard 2010; Wei et al. 2013). Moreover, the proposed methodological approach integrates the sustainable indicators into the system dynamic models (SDMs) to visualize their change along time and to assess how any variation on one indicator may lead to a series of responses on other indicators (Lacitignola et al. 2007; Jin et al. 2009; Liu et al. 2014). Besides, SDMs represent useful learning tools that enhance system understanding and facilitate involvement of non-technical stakeholders in the decision making processes (Costanza and Ruth 1998; Kelly et al. 2013).

In this work a dynamic model to contribute to a more balanced and multifunctional development of one insular SES: the Fuerteventura Biosphere Reserve sustainability model (FSM) is presented. Fuerteventura (The Canary Islands, Spain) represents one of the most arid environments in Europe, with a very low productivity and a particular fauna and flora with numerous endemic species, threatened by the recent tourist activities. This hyperarid and insular socio-ecological system represents a challenging case of study in order to compatibilice the tourist development with a sustainable management of its natural resources.

The specific aims of this work are: i) to develop an integral dynamic model of Fuerteventura island, which collects the factors and key processes of the socio-ecological system; ii) to include the most relevant sustainability indicators in the FSM and iii) to analyse the main changes and interactions between those factors and indicators.

3.2. METHODOLOGICAL APPROACH

3.2.1. Modelling process

The iterative process to elaborate the Fuerteventura sustainability model started with the development of a conceptual model, determining the factors and key processes of the sustainability of the system, their interactions and feedbacks (**Fig. 3.1**). The conceptualizing phase was carried out from the results of a workshop in the framework of the XI th. Atlantic Conference of the Environment, in which the most relevant themes for sustainability were identified with the participation of an experts panel. In relation to these results, a set of sustainability indicators was integrated in the model in order to facilitate the diagnosis and to analyse the progress and open challenges for the sustainability of the island. The indicators derive from a proposal of the Cabildo -the island council (Cáceres 2010)- and the Scientific Committee of the Fuerteventura Biosphere Reserve (pers. com.), in line with the sustainability aims of the AP (Action Plan 2013). Then, all model variables and parameters were defined and formulated starting from scientific literature and the available information. For parameters with no available data, an automatic calibration process was carried out (Oliva 2003). The FSM was calibrated for the 1996-2011 period, using 20 variables for which available observed data exist. Several model testing procedures were then applied, as it is explained in detail later.

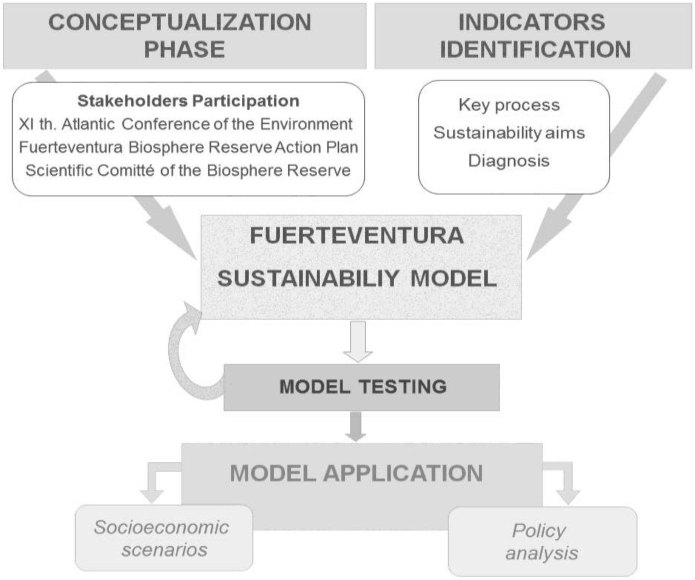

Figure 3.1. Simplified diagram of the methodological approach.

3.3. RESULTS

3.3.1. Model description

The model (**Fig. 3.2**) is structured in 5 sectors (Socio-tourist, Land Uses, Biodiversity, Environmental Quality and Water Resources). The 520 model variables include 22 state variables (**Table 3.1**) and 13 exogenous variables. 37 model variables represent environmental and socio-economic sustainability indicators which were integrated in the model (**Table 3.2**). 110 parameters have been identified in the model (**Table 5.2, Chapter 5**). The formulation of the model variables and parameter values can be consulted in Annex I.

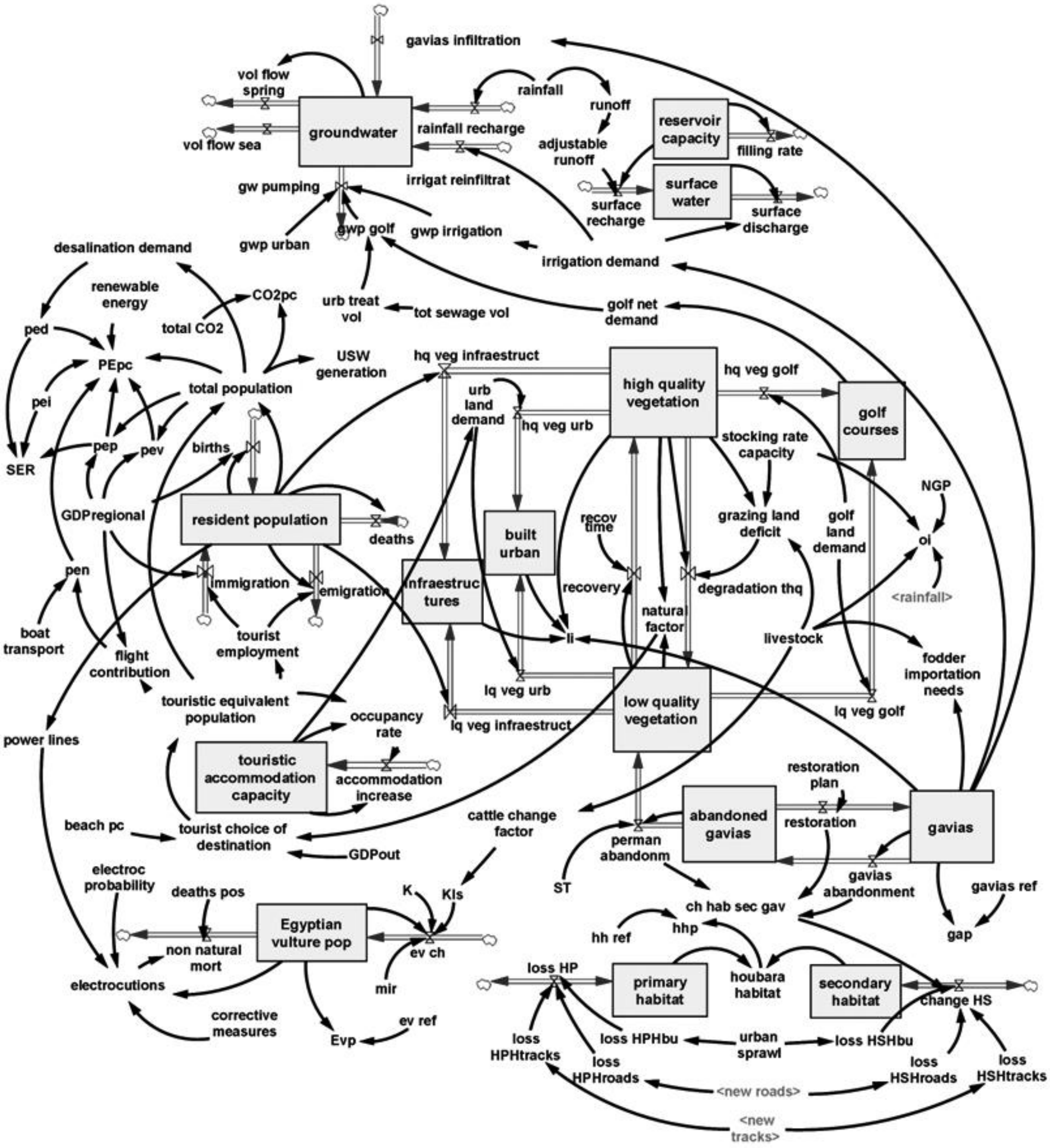

Figure 3.2. Overview of the Fuerteventura sustainability model, showing the key variables of the five sectors: socio-touristic, land uses, biodiversity, environmental quality and water resources.

Table 3.1. State variables included in the Fuerteventura Sustainability Model.

State variables	Definition	Units
resident population	Resident inhabitants.	inhabitants
tourist accommodation capacity	Tourist accommodation capacity (Hotels+ non hotels).	beds
hotel	Area occupied by hotel accommodations.	hectares (ha)
non hotel	Area occupied by non-hotel accommodations.	ha
residential	Area occupied by residential and other urban uses.	ha
golf courses	Area occupied by golf courses.	ha
trans hq natural veg	Area occupied by transformable high quality natural vegetation.	ha
notrans hq natural veg	Area occupied by non transformable high quality natural vegetation.	ha
low quality natural vegetation	Area occupied by low quality natural vegetation.	ha
abandoned gavias	Area occupied by abandoned gavias.	ha
fodder desalinated water supply	Capacity of desalination for fodder water supply.	m^3
gavias	Area occupied by active gavias.	ha
irrigation	Area occupied by irrigated lands.	ha
roads	Area occupied by roads.	ha
tracks	Area occupied by tracks	ha
primary habitat	Primary habitat of the Canarian Houbara Bustard.	ha
secondary habitat	Secondary habitat of the Canarian Houbara Bustard.	ha
Egyptian vulture pop	Egyptian vulture population.	number of Egyptian vultures
Groundwater	Groundwater volume.	m^3
surface water	Surface water.	m^3
reservoir capacity	Reservoir capacity	m^3
chGDPca	Cummulated annual change in the Canarian GDP.	dimensionless

Table 3.2. Sustainability indicators integrated in the FSM.

Sectors	Indicator	Units
Socio-Tourist	Population growth rate	%
	Population density	Inhabitants/km
	Occupancy rate	%
	Tourist attraction index	Dimensionless (dmls)
	Tourist choice of destination	dmls
	Ratio between tourist accommodation and resident population	dmls
	Tourist employment ratio	%
	Resident-tourist ratio	dmls
Land Uses	Artificial land proportion	%
	Non protected area with high environmental functionality proportion	dmls
	Fodder importation needs proportion	dmls
	Landscape indicator	dmls
	High quality vegetation area proportion	dmls
	Overgrazing indicator	dmls
	Roads density	km/km^2
	Beach *per capita*	m^2/inhab
Biodiversity	Houbara habitat proportion	dmls
	Egyptian vulture population proportion	dmls
	Key species deaths by electrocution	Individuals/year
	Protected area proportion	%
Environmental Quality	Motorization index	vehicle/inhab/year
	Share of renewable energy	%
	Per capita CO_2 emissions	Metric tonnes CO_2/ inhab/year

	Per capita primary energy consumption	GJ/inhab/year
	Per capita electric energy consumption	GJ/inhab/year
	Per capita USW generation	kg/ inhab/year
	Selective waste management index	kg/year
	Reciclyng rate of waste extracted from mix	%
	Per capita waste neither reused nor recycled	kg/inhab/year
Water Resources	Resident water consumption	m^3/inhab/year
	Tourist water consumption	m^3/inhab/year
	Total gross water demand	m^3/year
	Percentage of waste water treatment	%
	Percentage of waste water reused	%
	Energy consumption in seawater desalination	Kwh/year
	Losses in water distribution network	%
	Aquifer recharge	m^3/year

3.3.1.1. Socio-tourist sector

Tourism represents the main driving force of the employment and wealth generation in Fuerteventura. One of the key factors is the tourist equivalent population (*etp*), expressed as a function of the total annual tourist arrivals and the length of stay, which allows to asses the pressure of the tourism over the territory and the natural resources, independently of the seasonality (Patterson et al. 2008; BPIA 2012). Its modellization (**Eq. 3.1**) includes the tourist choice of destination (Hyde and Laesser 2009) which is calculated based mainly on: i) GDP evolution of the most important markets for outbound tourism for the island (Zhang and Jensen 2005; Garín-Muñoz 2006); ii) the tourist accommodation offer (Cruz 2009) -in relation to the occupancy rate and the reference capacity-, being the tourist accommodation capacity a state variable; and iii) tourist attraction index (Santana-Jiménez and Hernández 2011; Wei et al. 2013), based on three aspects: the available beach per capita, the natural vegetation factor and the tourist prices index of the island. Likewise, the effect of the so-called Arab Spring has been considered as an exogenous shock over the tourist arrivals (Canalis 2013).

$$etp = etp_i \cdot gdp_f \cdot ae \cdot b_{pc} \cdot nf \cdot tpi_f \cdot as \cdot tci_f \qquad \textbf{(3.1)}$$

where etp_i is the initial value of etp; gdp_f represents a factor based on the GDP of the most important markets for outbound tourism; ae is referred to the accommodation offer effect; b_{pc} represents the beach per capita factor; nf means the natural vegetation factor, which is the ratio between the actual and the initial area covered by natural vegetation; tpi_f is referred to the tourist prices index factor; as is the Arab Spring effect; and tci_f represents an automatic calibration parameter.

This sector includes another state variable: the resident population (**Fig. 3.3**). The migratory flows are strongly influenced by the employment offer in the tourist activities, which represents an average of 33% of the total employments in Fuerteventura (ISTAC 2012). Thus, the increase in *etp* leads to a raise in tourist employment and in other productive branches of the economy of the island, which has favoured the population growth and the demand of tourist and residential accommodations. This fact could affect some natural resources and services, eroding some aspects of the tourist attraction index, as the beach per capita factor or the natural vegetation factor. Thereby, the tourist choice of destination could be negatively affected even in destinies in development phase, as Fuerteventura Island, according to Butler's tourism destination cycle (Patterson et al. 2008). This example highlights the importance of the internal component given by feedback loops inside this sector, despite of the fact that tourist dynamic is largely driven by exogenous factors (von Bergner et al. 2014).

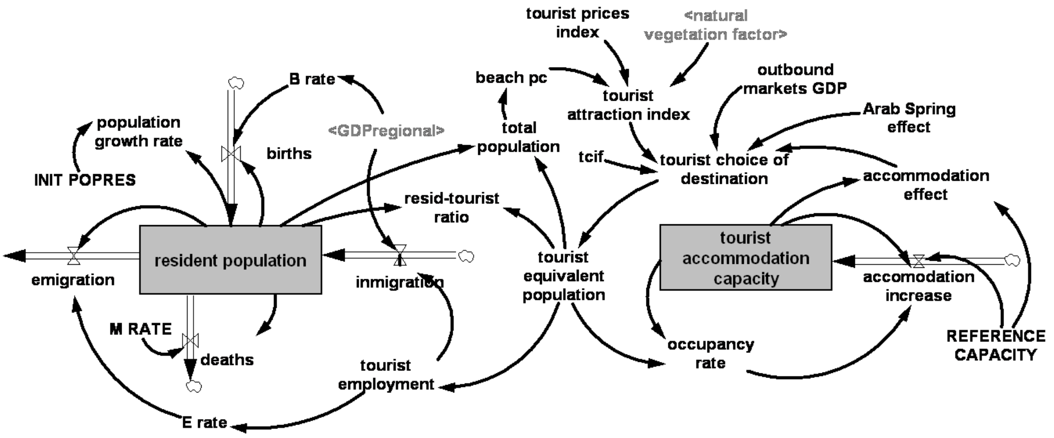

Figure 3.3. Simplified stock and flow diagram of the socio-tourist sector. The variables in grey colour belong to other model sectors.

3.3.1.2. Land use sector

This sector considers different uses of the land and their main changes along time. The included 12 state variables are gathered in 3 categories (**Fig. 3.4**): urban uses and infrastructures (residential, hotel and non-hotel tourist accommodation, golf courses, roads and tracks), agricultural (irrigation, active gavias and abandoned gavias) and natural, where high quality and low quality vegetation areas are considered, in terms of the potential (non altered) and actual vegetation according to the Canary Islands vegetation map (GRAFCAN 2011; del Arco et al. 2010). The protected areas and the Marine-Terrestrial Public Domain is considered in the model as non transformable high quality vegetation, since no land-use changes are allowed in these areas.

The increase in tourist and resident population has triggered the rise in built-up land -the area occupied by urban built-up and infrastructures (roads and tracks)-. Besides, Fuerteventura attends the gradual loss of traditional agro-systems, called gavias, whose abandonment gives way to irrigated crops. Nevertheless, gavias offer important environmental functions, such as landscape enhancement, increased rates of aquifer recharge and organic nutrients and water retention (Díaz et al. 2011). That is why the Cabildo has promoted the implementation of an Abandoned Gavias Restoration Plan (Fuerteventura Cabildo 2009).

As mentioned before, the island is facing a vegetation degradation problem. Some authors suggest that grazing is the main cause (Gangoso et al. 2006; Nogales et al. 2006; Schuster et al. 2012), whereas others state that grazing is highly desirable for the maintenance of certain species, thoroughly adapted to the presence of this ungulates (Arévalo et al. 2007; Fernández-Lugo et al. 2013). In our model the overgrazing effect on the high quality natural vegetation was formulated taking into account, on one side, the maximum -sustainable- stocking rate capacity offered by the insular territory, highly dependent of annual rainfall; and, on the other side, the proportion of livestock which actually grazes in Fuerteventura. When this overcomes the sustainable stocking rate capacity, the overgrazing indicator reaches values over 1, and the degradation of the high quality vegetation occurs (**Eq. 3.2**). Due to the fact that potential effects of this degradation (such as loss of aerial biomass, reduction of seeds and sprouts production, etc) will not be recovered immediately after the impact, the period of persistence of the effects was set up by an automatic calibration process around 4 averaged years.

$$oi = \left(\frac{ls \cdot ngp}{rf \cdot srf} \right) \tag{3.2}$$

where *oi* is the overgrazing indicator; *ls* is the livestock of the island; *ngp* is the net grazing proportion, this is the proportion of livestock needs which is not covered by supplementary food; *rf* represents the rainfall and *srf* is the stocking rate factor.

Another sustainability indicator of this sector is the landscape indicator (**Eq. 3.3**), which includes the positive aesthetic value of active gavias.

$$li = \left(\frac{hqv + gav}{bu + in} \right) \tag{3.3}$$

where *li* is the landscape indicator; *hqv* refers to the high quality vegetation area; *gav* means the area occupied by active gavias; *bu* means the urban built-up area; *in* is the area occupied by infrastructures (roads and tracks).

Two secondary succession processes are included in the model: first, the succession which takes place after the abandonment of agricultural areas, generating low quality natural vegetation; and second, the succession from low quality to high quality natural vegetation, which is much slower due to the hyperarid characteristics of the island.

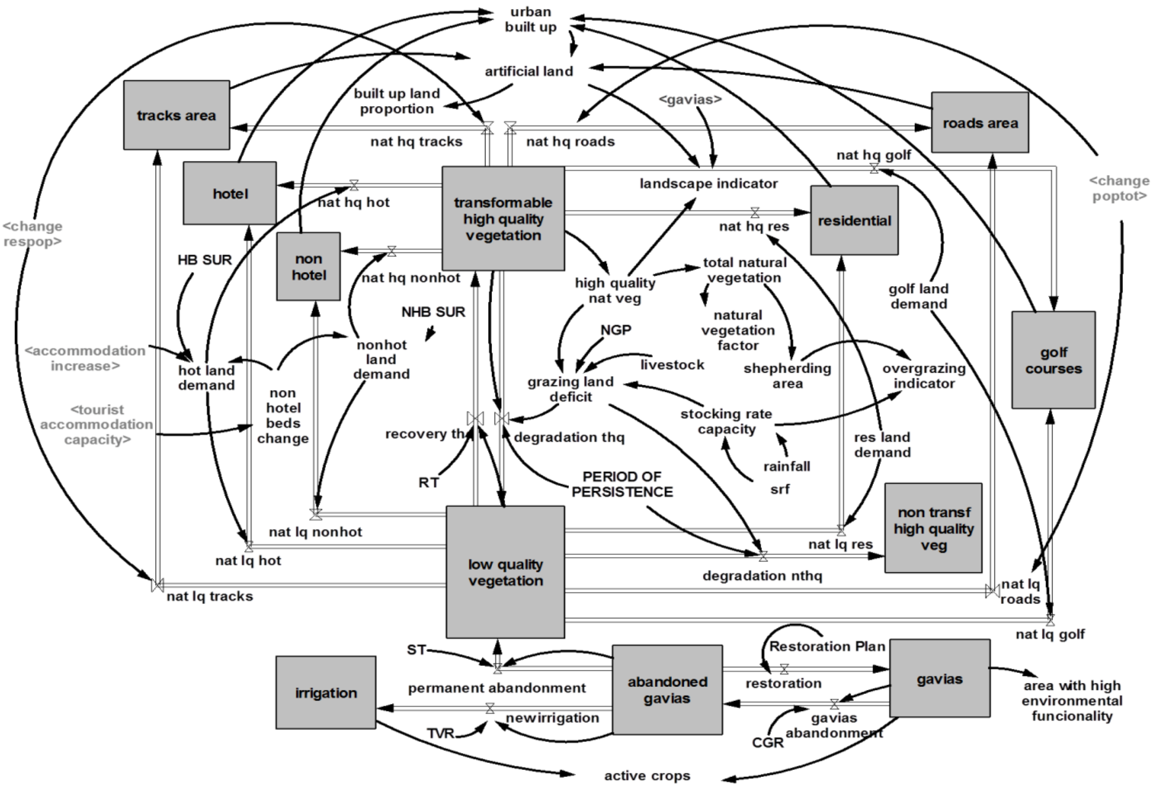

Figure 3.4. Simplified stock and flow diagram of the land uses sector.

3.3.1.3. *Flagship species sector*

In this version of the FSM, this sector (**Fig. 3.5**) is focused on two endangered species included in the National Catalogue of Threatened Species (BirdLife 2004; Lorenzo 2004) and endemic subspecies of The Canary Islands: the Canarian Houbara Bustard (*Chlamydotis undulada fuerteventurae*) and the Egyptian vulture (*Neophron percnopterus majorensis*). Both are very representative animal species of the island with a specific reference in the Action Plan of the Biosphere Reserve; therefore it is important to know to what extent changes which took place on the island have affected both species in the last decades. Although the use of these key species does not guarantee the conservation of the species richness (Carrascal et al. 2012), they are considered as flagship species which may facilitate the social support to biodiversity conservation policies (Walpole and Leader-William 2002; Verissimo and MacMillan 2011).

The habitat loss is the main threat factor for Canarian Houbara Bustard population on the island (Carrascal et al. 2008; Schuster et al. 2012). The two state variables which represent the potential habitat in the model, primary and secondary habitats -differentiated by the Houbara density they have-, are affected by the increase in urban areas and infraestructures related to tourist and urban development. The threatening factors for the habitat (urban uses, roads, tracks and active crops) and their specific ratios of change were defined according to Carrascal et al. (2008). See chapter 6 for details. On the other hand, the abandoned gavias constitute the secondary habitat of the Houbara.

The population of Egyptian vulture was modelled considering denso-dependence factors and the effect of livestock, which increases the island carrying capacity to host this scavenger **(Eq. 3.4)**. Its main threat factors are poisonings and electrocutions (Donázar et al. 2002; Palacios 2004). The factors which influence the electrocution probability were also considered, including stochastic and determinist components, such as implementing corrective measures in power lines. The change in the Egyptian vulture is expressed as:

$$ech = \left(ev \cdot mir \cdot \frac{k + k_{ls} - ev}{k + k_{ls}} \right) - \left(\left(ep \cdot pli \cdot ev + f_{stk} \right) + pos \right) \tag{3.4}$$

where *ech* is the annual change in Egyptian vulture population; *ev* represents the population of the Egyptian vulture; *mir* is the maximum or intrinsic growth ratio for the Egyptian vultures; *k* is referred to the Egyptian vulture carrying capacity without considering the livestock effect; k_{ls} is the additional carrying capacity generated by the existence of livestock; *ep* means the probability of electrocution; *pli* concerns the length of power lines on the island; f_{stk} represents the stochastic factor included in the electrocution probability; *pos* refers to poisonings.

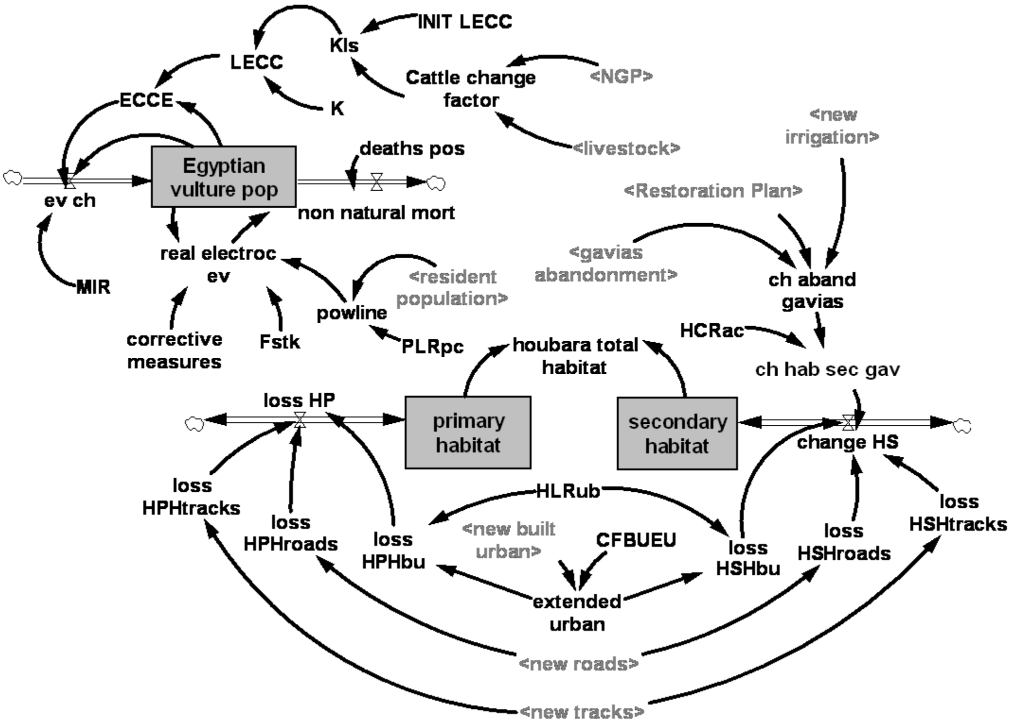

Figure 3.5. Simplified stock and flow diagram of the flagship species sector.

3.3.1.4. Environmental Quality sector

This sector encompasses both the energy generation and consumption, and the waste production and management (**Fig. 3.6**). The different energy demands –from tourist equivalent population, resident population, transport, productive activities and the energy consumed by the desalination process- were taken into account. The increase in the regional GDP leads a rise in the per capita electric consumption ratio, as well as in the motorization index. The model also allows to calculate the energy self-suffiency indicator (the share of renewable energy, **Eq. 3.5**) in order to analyse the proportion of the total energy demand covered by renewable resources (Denis and Parker 2009; Chester 2010), which on the island are, mainly: wind power, solar thermal and photovoltaic.

$$ser = \frac{wp + thp + php}{pep + pet + pei + ped} \qquad \textbf{(3.5)}$$

where *ser* is referred to the share of renewable energy; *wp*, *thp* and *php* are the energy produced by renewable resources: wind power, thermal power and photovoltaic power, respectively (in GJ/year); *pep*, *pet*, *pei* and *ped* are the primary energy demand from population (resident and tourist), transport, productive activities and the seawater desalination, respectively (in GJ/year).

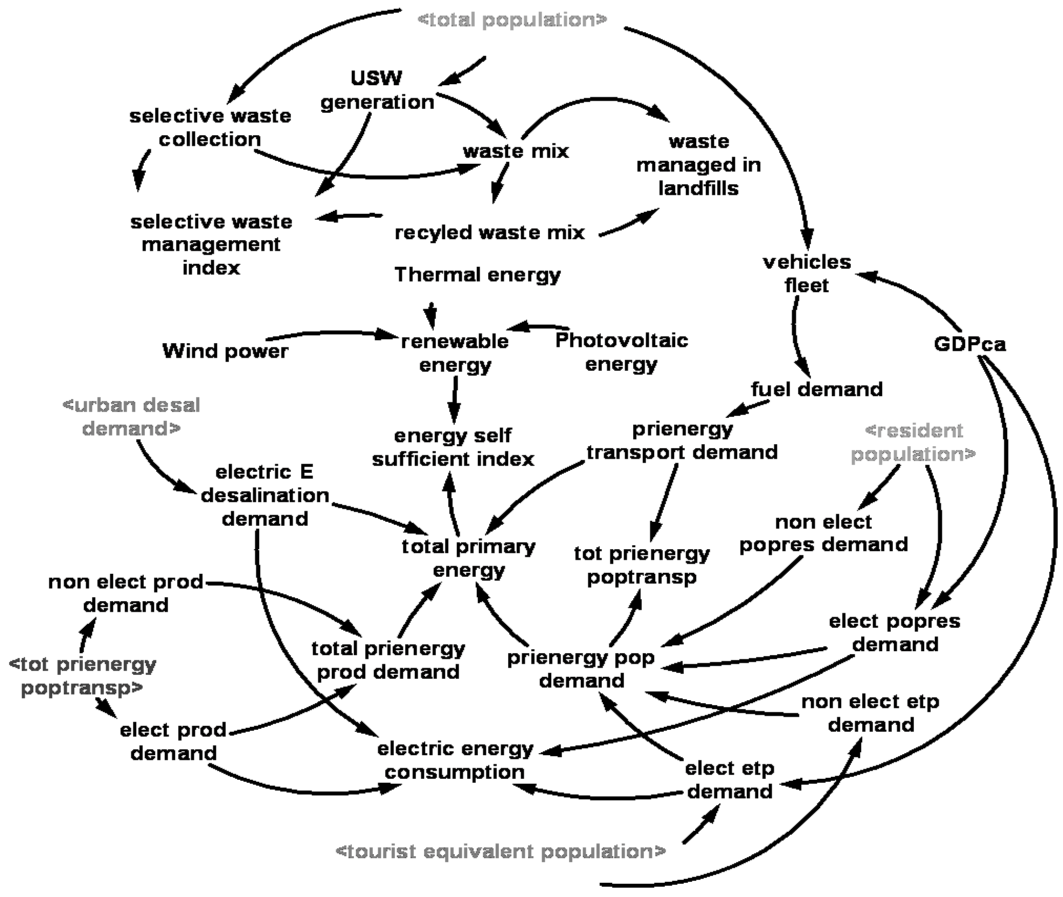

Figure 3.6. Simplified stock and flow diagram of the environmental quality sector.

Regarding the urban waste management, the efficiency of the separation and the recycling, and the quantity of wastes left in the dump were considered. By means of the selective waste management index, the proportion of the generated urban waste which is actually recycled may be analysed, as a key component of the sustainability of the island (Cáceres 2010).

3.3.1.5. Water resources sector

In the case of Fuerteventura island, water resources scarcity traditionally represented one of the limiting factors for the island development and, particularly, its tourist development. Nevertheless, the technological advances in relation to seawater desalination have favoured the overcome of this key limitation in a hyperarid island.

This model sector consists of 3 state variables: groundwater, surface water and the reservoir capacity (**Fig. 3.7**). The total gross water demand indicator has been built taking into account the differentiated demands of: livestock, irrigation, golf courses, resident and tourist consumption (**Eq. 3.6**). The surface resources are not enough to satisfy the increasing population demands or the irrigation requirements. The groundwater resources, dominantly brackish (Herrera and Custodio 2000), are aimed at agricultural and farming uses, which must be desalinated before being used. This gives an idea of the importance of the roll played by the desalination to cover the total water demand (Cabrera and Custodio 2012), as well as the importance of the water supply on the sustainability of a tourist island (Deyá and Tirado 2011).

$$gwd = \sum_{i=1}^{n}(h_i \cdot d_i) + \sum_{j=1}^{m}(s_j \cdot r_j + l_j) + \sum_{k=1}^{p}(ih_k \cdot c_k + f_k) \qquad \textbf{(3.6)}$$

where *gwd* is the total gross water demand indicator; h_i is the number of heads of *n* number of *i* class of livestock (caprine, ovine, bovine and porcine); d_i means the water consumption rate of each class of livestock *i* (m^3/cattle head); s_j refers to the area (in hectares) of *m* number of *j* land uses (irrigation crops and golf courses); r_j is the water consumption of each *j* land use (in m^3/ha); l_j means the conveyance losses of each *j* land use; ih_k is the number of inhabitants of *p* number of *k* groups (resident and tourist equivalent population); c_k means the water consumption of each *k* group (in m^3/inhabitant); f_k is referred to the water distribution and transport losses (in m^3/year).

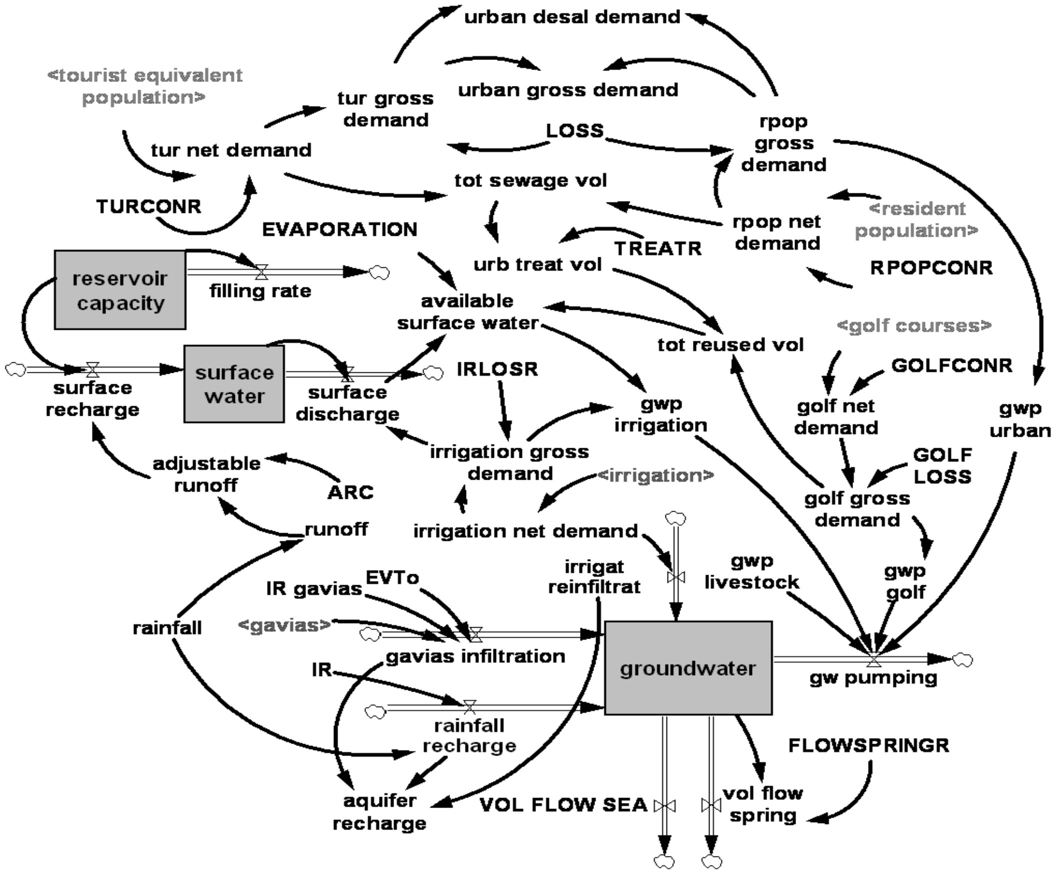

Figure 3.7. Simplified stock and flow diagram of the water resources sector.

3.3.2. Model Testing: methods and results

A set of model testing procedures was applied (Barlas 1996), including: dimensional consistency test, sensitivity analysis, extreme conditions test and goodness of fit test for the 20 variables with available observed data series. The model successfully passed such testing procedures.

The sensitivity analysis, very useful to assess the model robustness (Loehle 1997; Graham et al. 2002), was carried out on the parameters set by automatic calibration, of which only one -related to the tourist choice of destination- showed a high sensitivity. In relation to extreme condition tests (Li et al. 2012), the model generates the expected results when it is subjected to 25 extreme conditions such as an unexpected drop of the tourist arrivals, an accelerated demand of built-up land, extreme droughts, total elimination of the Abandoned Gavias Restoration Plan, or an increase in grazing (**Annex II**). Some of these examples are shown as follows:

-Drop of the tourist arrivals leads to a reduction of employment.

TEXT DESCRIPTION: Unexpected drop of the tourist arrivals along five years (“etp dec”) would lead to a reduction of employment (“touristempl”).

VENSIM SYNTAXIS:

TEST INPUT: “etp dec”: etp=RC RAMP (etp, 0.5, 5, 1998)

CONSTRAIT: CONDITION: “etp dec”: IMPLIES: “touristempl”<=RC RAMP CHECK (0, “touristempl”, 0.5, 7, 1998)

TESTS RESULTS: **Figure 3.8**

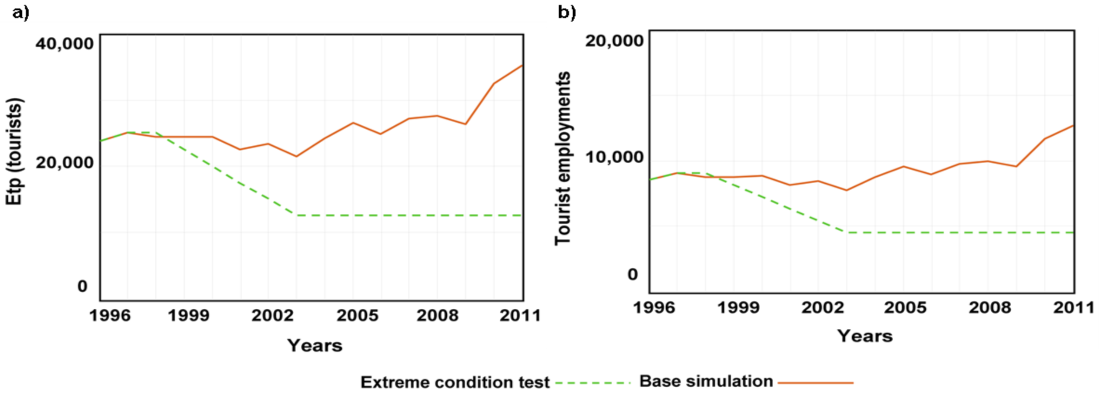

Figure 3.8. Simulation of the extreme condition test: "*Drop of the tourist arrivals leads to a reduction of employment*". a) Input conditions; b) Expected effects.

- *Extreme droughts lead to overgrazing.*

TEXT DESCRIPTION:

If the annual average rainfall was kept below or equal 40 mm, the overgrazing indicator would reach values over 1 after some years.

VENSIM SYNTAXIS:

TEST INPUT: rainfall<=40 mm

CONSTRAIT: CONDITION “rainfall<=40 mm”: IMPLIES: “overgrazing indicator<1”

TESTS RESULTS: **Figure 3.9**

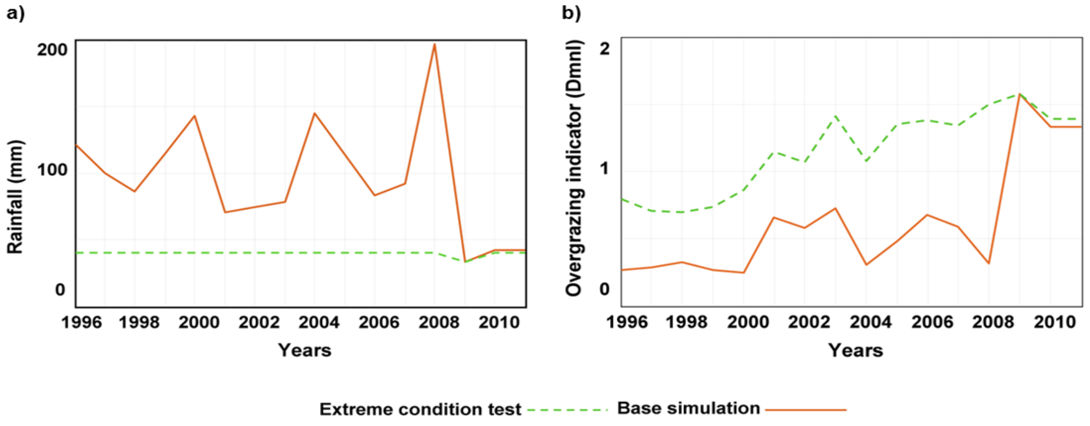

Figure 3.9. Simulation of the extreme condition test: "*Extreme droughts lead to overgrazing*". a) Input conditions; b) Expected effects.

- *An accelerated demand of built-up land leads to a reduction on houbara habitat*

TEXT DESCRIPTION:

If built up urban demand would boost for three years, a loss of houbara habitat would be expected.

VENSIM SYNTAXIS:

TEST INPUT: “TI built urban dem increases”: built urban=RC RAMP (built urban dem, 6, 3, 1998)

CONSTRAIT: CONDITION “TI built urban dem increases”: IMPLIES: habitat total hubara<=RC RAMP CHECK (3, habitat total hubara, 0.8, 5, 1998)

TESTS RESULTS: **Figure 3.10**

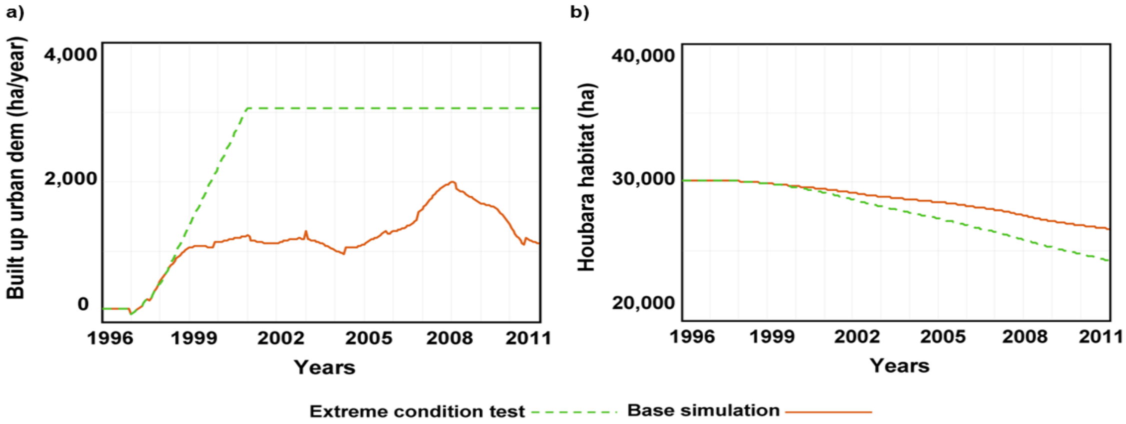

Figure 3.10. Simulation of the extreme condition test: "*An accelerated demand of built-up land leads to a reduction on houbara habitat* ". a) Input conditions; b) Expected effects.

The comparison of the simulation results to the observed data constitutes a measure of the goodness of fit and, therefore, the ability of the model to track the actual behaviour of the system and to capture its key questions (Solecki and Oliveri 2004; Martínez-Moyano and Richardson 2013). In this work, the mean absolute percentage error (MAPE, **Eq. 2.6**), calculated according to Goh and Law (2002) and Oliva (2003), and the normalised root mean square error (NRMSE, **Eq. 2.7**), according to Andarizan et al. (2011), Ganderson and Price (2012) and Sepaskhah et al. (2013), were determined.

Results for the 20 variables with available observed series show similar values for both statistics. **Table 3.3** shows the average values of MAPE and NRMSE for the 20 variables, the fraction of the error that is due to unequal means (U^M), unequal variances (U^S) or imperfect correlation (U^C), and the number of variables included in the intervals, according to the goodness of fit results.

A total of 14 variables have a mean absolute percentage error below 10%, which is considered an excellent degree of fit (Goh and Law 2002), whereas 4 variables achieve a good degree of fit (MAPE between 10-20%). Only two variables, immigration and emigration, has a degree of fit only acceptable according to these authors (MAPE between 20-30%), which might be related to the lack of reliability of this observed data series.

Regarding the NRMSE calculation, 12 variables present an excellent degree of fit according to Andarizan et al. (2011) and Sepaskhah et al. (2013), who stated the same intervals, 5 variables achieve a good degree of fit, and 3 variables achieve an acceptable degree of fit: immigration, emigration and golf courses.

These statistics allow to quantify not only the magnitude of the error but fundamentally the nature of the error, in particular whether or not it is a systematic error. Regarding the confidence in the model, the error should be small, and in the case of not negligible errors, it should not be concentrated in U^M (bias) nor U^S (unequal variance), but in U^C (incomplete covariation) (Sterman 1984). In the case of the three variables with only acceptable degree of fit (MAPE or NRMSE between 20-30%), most of error is due to incomplete covariation.

It can be concluded that the results of the model testing procedures point to a high degree of fit between simulation results and observed series, which supports the ability of the model to track the behaviour of the SES of Fuerteventura.

Table 3.3. Detailed results of the goodness of fit test for the 20 variables with available observed data series.

VARIABLES	n	MAPE (%)	NRMSE (%)	U^M	U^S	U^C
Resident population	16	4.300	5.458	0.272	0.006	0.722
Births	12	6.220	8.624	0.340	0.067	0.593
Inmigration	16	26.184	23.384	0.069	0.275	0.657
Emigration	16	32.699	31.650	0.001	0.428	0.571
Tourist equivalent population	16	9.517	12.035	0.08	0.0	0.92
Tourist accommodation capacity	16	7.287	9.400	0.478	0.067	0.455
Occupancy rate	16	8.705	10.847	0.19	0.012	0.798
Tourist employment	13	5.386	6.634	0.525	0.0	0.475
Houbara habitat	3	0.979	1.531	0.423	0.019	0.558
Egyptian vulture population	13	4.539	5.080	0.001	0.021	0.978
Urban built-up	16	2.335	2.840	0.04	0.0	0.959
Tracks	3	1.059	1.730	0.354	0.086	0.561
Roads	3	0.714	1.051	0.452	0.104	0.451
Active crops area	15	10.137	11.398	0.016	0.453	0.532
Irrigated crops area	15	11.755	13.698	0.050	0.66	0.29
Active gavias area	15	10.492	11.550	0.149	0.537	0.315
Natural vegetation area	3	0.280	0.446	0.378	0.587	0.035
Golf courses area	15	10.01	24.45	0.004	0.143	0.982
Vehicles fleet	12	4.574	4.145	0.574	0.184	0.242
Electric energy consumption	14	4.977	7.142	0.093	0.012	0.894

n: Number of observed data.

3.3.3. Simulation Results

The model testing results offer an adequate degree of model confidence to use it as a tool to analyse the changes in the main sustainability issues of Fuerteventura.

Regarding the socio-tourist sector, the tourist equivalent population (*etp*) shows a rising trend during most of the simulation period (**Fig. 3.11a**). Nonetheless, since the economic crisis began in 2008, with a major impact on GDP factor, a sharp drop of the tourist arrivals in 2009 was produced and, therefore, a fall of the tourist employment took place (**Fig. 3.11b**). Since then, several factors have driven the recuperation of the *etp* and the occupancy rate (**Fig. 3.11c**): i) the beginning of the economic recovery in the main markets that provide tourists bound to Fuerteventura; ii) the contraction of tourist prices on the island; and iii) the consequences of the Arab Spring revolts on the tourism. Nevertheless, the recovery of the employment has not been as immediate as the tourist arrivals. In fact, the recession has produced a deep change in job creation, with a reduction of jobs per tourist ratio.

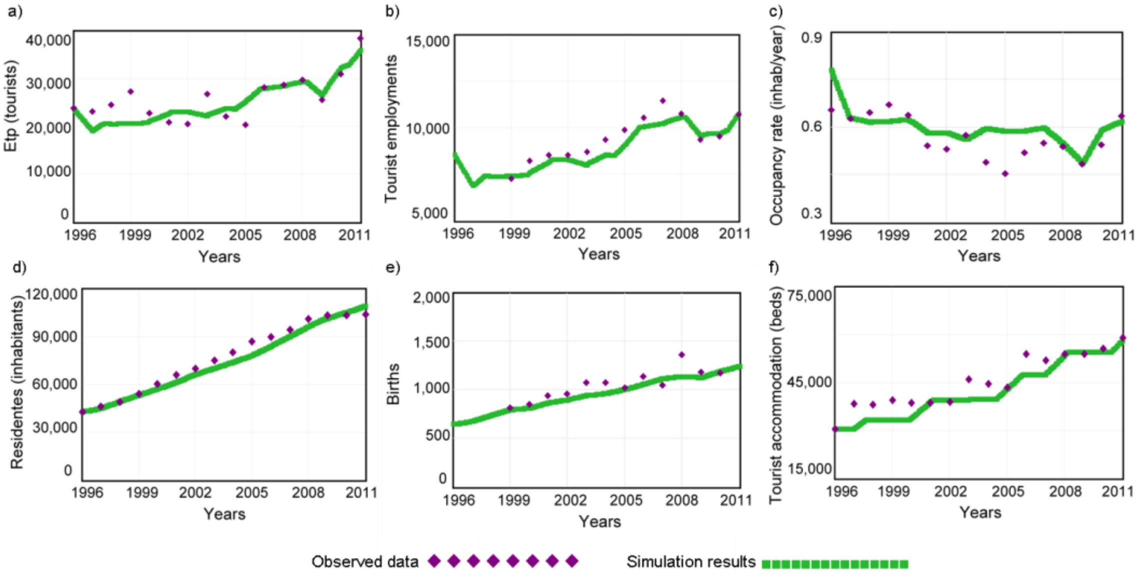

Figure 3.11. Observed data and simulation results between 1996 and 2011. a) Tourist equivalent population (*etp*). b) Tourist employment. c) Occupancy rate (hotel and non-hotel accommodation). d) Resident population. e) Births. f) Tourist accommodation. Observed data source: ISTAC (2010).

The tourist activity is one of the key factors in the extraordinary population growth which has taken place in Fuerteventura. The resident population has doubled in only 10 years (1996-2006), beating 100,000 residents in 2011 (**Fig. 3.11d**). This trend is not only explained because of the strong vegetative growth (with a birth rate over the national average, **Fig. 3.11e**), but it is mainly due to a positive migratory flow (**Fig. 3.11f)** driven by the increase in the employment. This trend in the tourist activity of the island has also triggered the offer of tourist accommodations, which has almost tripled during the simulation period (**Fig. 3.11g**).

The rise in both resident and tourist equivalent population represents a driving factor for the land use sustainability indicators. Among them, the proportion of built-up land respect to the total insular area can be highlighted (Spilanis et al. 2009; BPIA 2012), since land uptake constitutes one of the changes promoting unsustainable processes at broad scales, despite the apparently modest values respect to total land. Even though the proportion of built-up land does not exceed 6% of the total island area, the urban built-up area has tripled along the simulation period (**Fig. 3.12a**).

On the other hand, a more sustainable and efficient use of land requires the maintenance of environmentally active natural and rural systems. According to this aim, which is explicitly addressed in the Fuerteventura Biosphere Reserve Action Plan, the FSM includes the proportion of active gavias, considered as a key indicator. Socioeconomic changes have led towards a progressive abandonment of gavias. This trend has suffered an important change since 2002, due to the timely plans of gavias restoration. Without these plans, the area of active gavias would have been around 50% less at the end of the simulation period. Despite the increase in the area of active gavias, the landscape indicator tends to decrease mainly due to the increase in the proportion of the built-up land (**Fig. 3.12b**).

Fuerteventura still maintains a high proportion of the insular area covered by natural uses. Along the simulation period, the net loss of natural land (both high quality and low quality vegetation) is 5,324 ha, which means around 3.5% of the initial value. However, the Scientific Committee of the Reserve (pers. com.) stands that the degradation of the vegetation represents one of the most worrying processes. In particular, some authors suggest that grazing could be one of the drivers of this degradation (Gangoso et al. 2006; Nogales et al. 2006; Schuster et al. 2012). According to the simulations results, the model does not support the existence of a continued vegetation degradation caused by the livestock during this period, since the overgrazing indicator maintains, in general, values below 1 (**Fig. 3.12c**). In contrast, it seems that, during especially intense droughts, such as the one that took place between 2009 and 2010, there would be a degradation of high quality vegetation due to overgrazing, whose effects might remain for some years.

Figure 3.12 also shows the comparison between observed data and simulation results for the area occupied by: roads and tracks (**Fig. 3.12d**), the total natural vegetation and crops (**Fig. 3.12e**) and the irrigated lands and golf courses (**Fig. 3.12f**).

The effects of land uptake and fragmentation represent one of the main threatening factors for the biodiversity of the island and, in particular, for the potential habitat of the Canarian Houbara. Simulation results show an adequate fit to estimated values from literature and available cartographic information (years 1996, 2002 and 2010). **Figure 3.13a** shows the reduction of the potential Houbara habitat, as a result of disturbances caused mainly by the rise in the land uptake. The decrease in abandoned gavias, mainly due to the restoration plan, has also favored the habitat loss since abandoned gavias constitute secondary habitat for Houbara.

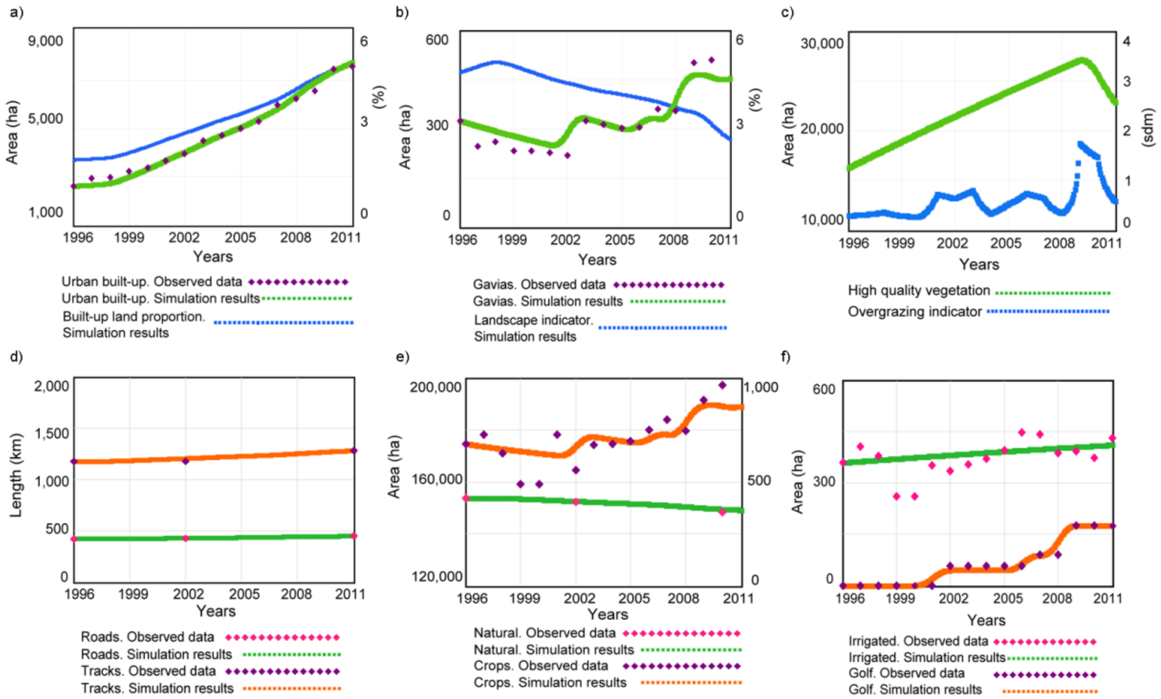

Figure 3.12. Observed data and simulation results between 1996 and 2011. a) Urban built-up and built-up land proportion. b) Active gavias area and landscape indicator between 1996 and 2011. c) High quality vegetation and overgrazing index (simulation results). d) Roads and tracks. e) Total natural vegetation and crops (second axis). f) Irrigated lands and golf courses. Observed data source: ISTAC (2013), Cadastre (2012) and GRAFCAN (2011).

The population of the Egyptian vulture has increased during the simulation period, directly related to the rise in cattle herd and to the reduction of the electrocutions since 2006, thanks to the implementation of management measures aimed at decreasing the mortality in power lines. As shown in **Figure 3.13b**, without a rise in the livestock grazing on the island, the number of Egyptian vultures would have been around 33% smaller at the end of the simulation period.

In relation to the energy issues, the total electric energy consumption has increased (**Fig. 3.14a**), due to the rise in the per capita electric consumption ratio related to the regional GDP and an increase in the total population (both resident and tourist equivalent). Likewise, the rise in the regional GDP is also related to the vehicles fleet (**Fig. 3.14b**) and, therefore, the motorization index and the transport energy demand.

Figure 3.14c shows a decrease in the energy self-sufficiency indicator along the simulation period since, despite some moderate rise in renewable energy sources in Fuerteventura, the increase in the total primary energy demand has been much higher.

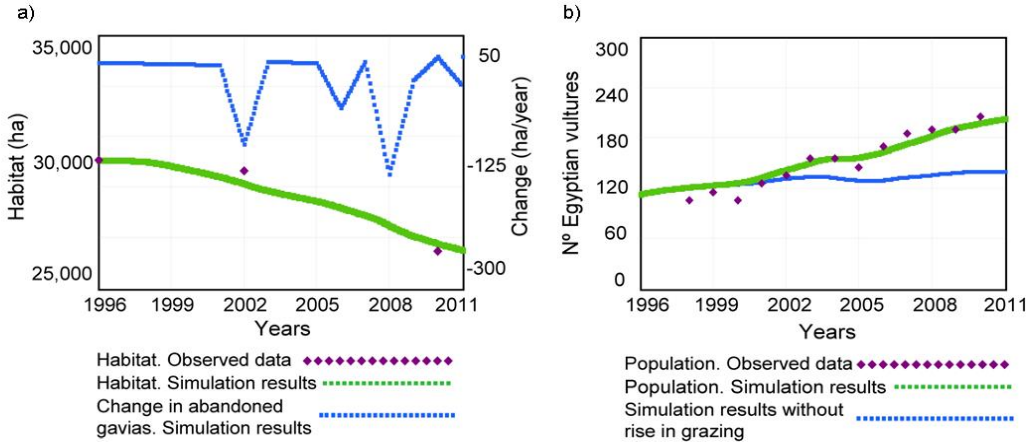

Figure 3.13. Observed data and simulation results between 1996 and 2011. a) Houbara potential habitat and change in abandoned gavias (simulation results). b) Egyptian vulture population and simulation results of the Egyptian vultures under the hypothesis of no rise in grazing. Observed data sources for Houbara potential habitat estimated from: 1996, Lorenzo et al. (2004); 2002, Carrascal et al. (2008); 2010, Schuster et al. (2012).Observed data sources for Egyptian vulture population: 1998, Palacios (2000); 1999-2001, Donázar et al. (2002); 2002-2007, Díez et al. (2008); 2008-2010, Mallo and Díez (2009, 2010).

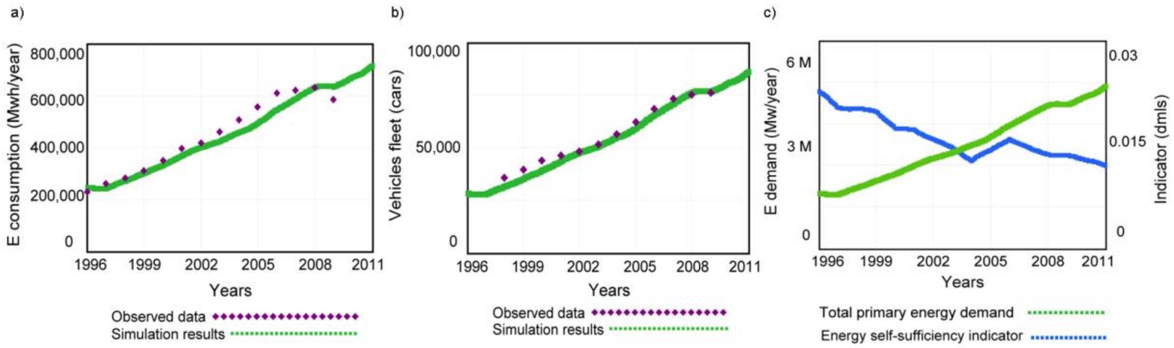

Figure 3.14. Observed data and simulation results between 1996 and 2011. a) Electric energy consumption. b) Vehicles fleet. c) Simulations results of the total primary energy demand and the energy self-sufficiency indicator. Observed data source: Special Territorial Plan for Energy Facilities Management (PTEOIEFV 2008).

Regarding water resources, there is a noticeable lack of observed data series. Nevertheless, values and ranges of simulation results are consistent with the available scattered information. **Figure 3.15a** shows the demands from the considered sectors: population (resident and tourist equivalent) represents the biggest proportion of the demand, 69% of the total demand (around 12.5 Hm^3 in 2011). The net consumption per resident was 180 litres per person and day (**Fig. 3.15b**); while tourists consumed around 378 litres and 221 litres per person and day in hotels and non-hotel tourist accommodations, respectively (CIAFV 2009). The demand of golf courses, irrigation and livestock demands correspond to around 2.31, 3.45 and 0.23 Hm^3/year, respectively, at the end of the simulation period. **Figure 3.15c** shows the total water demand and the different water sources. Surface water and groundwater pumping are clearly insufficient to fit the total water demands, covering around 20% in average. Therefore seawater desalination is required to satisfy the remaining demand.

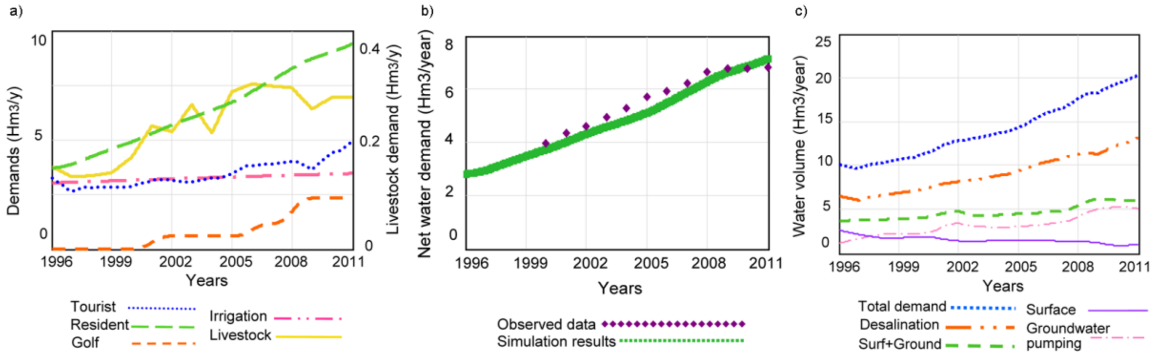

Figure 3.15. a) Gross water demand per sectors. Simulations results for period 1996-2011. b) Net water demand by resident population. Observed data and simulation results between 1996 and 2011. c) Total demand and available water per source. Simulations results for period 1996-2011. Where: Tot demand: total gross water demand of all sectors; Desalination: seawater desalination; Surface: regulated surface water coming from the reservoir; Groundwater: total groundwater pumping; Surf+Ground: surface water plus groundwater pumping. Observed data source: HPF (2013).

3.4. DISCUSSION

The Fuerteventura sustainability model allows to understand the main components of this socio-ecological system and their changes along time, as well as the synergies and interactions between sustainability indicators and other factors, which may help to improve the diagnosis and decision-making processes as well as the assessment of sustainable policies.

Regarding the flagship species sector, the model has allowed to analyse the change in two key endangered species, linked to the dynamics of their main threatening factors. This analysis is required to develop strategies for their protection (Feld et al. 2010). In order to reduce the Houbara habitat loss, one of the measures which could be considered might be the elimination of the Abandoned Gavias Restoration Plan, since abandoned gavias are part of its secondary habitat. Nevertheless, active gavias constitute a traditional agro-system which positively contributes to the scenic quality of the landscape, whereas their morphology favors the organic nutrients and soil water content, contributing to the natural fertilization of the crops and the aquifer recharge (Hernández-Moreno et al. 2007; Díaz et al. 2011). The simulation results (**Table 3.4**) support the existence of some trade-offs between environmental aims under the same management measure, in which the optimization of some aims implies the reduction of others (MEA 2005; Rodríguez et al. 2006; Vidal-Legaz et al. 2013). Although the impact of the Restoration Plan is limited during the study period (around 400 restored hectares) and does not imply noticeable changes in the mentioned indicators, this trade-off might become of concern under more extensive plans of gavias restoration. Therefore, the developed FSM could be useful to quantify the relative magnitude of these and other trade-offs.

Many experts point to the urgent need for a stronger control on the loss of high quality vegetation. Some authors claim that grazing could be one of the triggers of the degradation in The Canary Islands (Nogales et al. 2006; Garzón-Machado et al. 2010; Schuster et al. 2012); whereas others state that grazing is highly desirable for the maintenance of certain species, adapted to the presence of these ungulates (Arévalo et al. 2007; Fernández-Lugo et al. 2013). In relation to this issue, the model results do not support the existence of a continuous overgrazing on the island. However, during severe droughts, the grazing requirements do exceed the stocking rate capacity and, therefore, the vegetation degradation takes place. In order to avoid these potential episodes, whose effects over the vegetal species composition and the landscape indicator may remain for some years, some authors claim the need for measures to control the livestock. Nonetheless, a mere cattle herd reduction might lead to negative impacts on the insular population of scavengers, such as the endangered Egyptian vulture (Donázar et al. 2002; Gangoso et al. 2006). As **table 3.4** shows, if the grazing had not increased during the study period, the Egyptian vulture population would not have exceeded 140 specimens, which would suppose a more critical threat status and more expensive conservation measures would be necessary to avoid its extinction.

Table 3.4. Comparison of results for 6 sustainability indicators (gavias, landscape indicator, aquifer recharge, net grazing proportion, average overgrazing index in drought period (2009-2010), high quality vegetation area and Egyptian vulture population) under the base simulation (column 1), expected results if no gavias restoration is implemented (column 2) and if no grazing rise takes place, which would suppose that net grazing remains at 3,500 LU, as at the beginning of the simulation period, instead of around 7,700 LU (column 3).

Index indicator	**Measures**		
	Base simulation	Simulation without gavias restoration	Simulation without grazing rise
Gavias (Ha)	453.23	150.78	453.23
Landscape indicator (dml)	2.68	2.64	3.34
Aquifer recharge (Hm^3)	12.63	12.13	12.63
Overgrazing index in drought period (dml)	1.60	1.60	0.77
High quality vegetation (Ha)	22.87	22.90	28.66
Egyptian vulture population (nº)	203	203	140

The water-energy binomial offers another trade-off regarding sustainable development. Whereas the seawater desalination, the main source of water on the island, has enabled to overcome the limitations of water scarcity on the socioeconomic activities, its negative side –a high energy consumption, an increased energy dependence and greenhouse and brine emissions- must be addressed (Meerganz von Medeazza and Moreau 2007; Lattemann and Höpner 2008; Melían-Martel et al. 2013), particularly in an insular system with a low and decreasing self-sufficiency indicator, as aforementioned (**Fig. 3.14c**). This dependence on allocthonous, non renewable energy resources on Fuerteventura is rising, which represents a clear sign of unsustainability. Even more, the strong dependency of water availability on energy consumption -80% of total water demand is covered by seawater desalination-, implies a high vulnerability of the whole socio-ecological system, even for basic needs, to socioeconomic changes such as those in the energy policies and markets, and to the ongoing global change (Kruyt et al. 2009).

The existence of potential trade-offs between environmental aims as well as between socioeconomic development and conservation options, as described above, should be taken into account in the decision-making in order to achieve a more sustainable management of any socio-ecological system (Rodríguez et al. 2006; Su et al. 2012; Moeller et al. 2013; Vidal-Legaz et al. 2013).

The difficulties to achieve the sustainability goals lie on the complex cause-effect relations which determine the socio-ecological systems behavior. In this sense, the catalogues of sustainability indicators, traditionally applied in a static way (Prescott-Allen 2001; Spangenberg 2002), have important shortcomings, given their inability to address this complexity and interactions between indicators, which might lead to a biased assessment of the diagnosis and options. Only coping with this complexity, these trade-offs can be identified and quantified as input for a decision-making process. In this context, SDMs provide a useful tool to improve the integral diagnosis of the socio-ecological problems and, therefore, to reduce the conflicts between management options (Kelly et al. 2013).

This Fuerteventura sustainability model presents some shortcomings. On one side, it has a limited reusability, a principle claimed in environmental modelling activities (Granell et al. 2013), since it has been developed using a context-specific approach, as many other integral models (in the sense of Voinov and Shugart 2013). Moreover, an extension of the binomial water-energy issues is needed in order to improve the diagnosis of this important component of the sustainability in Fuerteventura. However, I do support the need for problem-specific perspectives to deal with the complexity of each real SES, as other studies have proposed (Jin et al. 2009; Li et al. 2012; Marín et al. 2012; Martínez-Fernández et al. 2013), and has also been showed in this work.

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CHAPTER 4

Using dynamic sustainability indicators to assess enviromental policy measures in biosphere reserves

4. USING DYNAMIC SUSTAINABILITY INDICATORS TO ASSESS ENVIROMENTAL POLICY MEASURES IN BIOSPHERE RESERVES*

Abstract

The assessment of different policy options represents a major tool for decision-makers in Biosphere Reserves, to develop more resilient strategies for sustainable development and to visualize unintended consequences of these policies.

In this work eight measures, proposed in order to meet the main objectives of environmental sustainability are analysed, which are collected in the Action Plan of the Fuerteventura Biosphere Reserve (Spain). A set of ten environmental indicators, also proposed by the Action Plan, was used, which was integrated in the Fuerteventura Biosphere Reserve sustainability model (FSM). Their behaviours under these measures allow to determine whether the objectives would be met along 2012-2025. Although some indicators would improve under these measures, fitting certain objectives, some negative effects on other indicators confirm the existence of trade-offs among these objectives. For instance, the measure of grazing limitation would improve the proportion of high quality vegetation but would negatively affect the Egyptian vulture population which would even exceed its sustainability threshold. The definition of thresholds for each indicator allows decision-makers to establish a way to prioritize among the eight analysed measures. Results show that these measures are insufficient to meet the sustainability thresholds of four indicators (the landscape indicator, the proportion of renewable energy, the per capita primary energy consumed and carbon dioxide emissions).

Focusing on the remaining six indicators and following the rule “Threshold out, measure out”, seven out of eight measures would exceed some thresholds and should be avoided. Only one option, aimed at cropping fodder for feeding the cattle on restored traditional agricultural lands, would not exceed any of these thresholds. However, this measure also presents certain negative effects over some indicators related to flagship species (the houbara habitat and the Egyptian vulture population), which would require compensation measures.

This work shows the application of integral tools to: i) analyse the measures proposed by different agents and actions plans, ii) quantify their effects in terms of sustainability thresholds of selected indicators, iii) identify side-effects and trade-offs among environmental objectives, iv) determine the degree of uncertainty of the simulation results, v) prioritize among measures and vi) identify non-addressed objectives by the proposed measures.

Keywords: system model; integral approach; environmental objectives; sustainability thresholds; trade-offs.

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4.1. INTRODUCTION

Biosphere Reserves (BRs) provide an example of an integrated sustainability framework which explicitly acknowledges that complex socio-economic and ecological systems are inextricably linked (Levrel and Bouamrane 2008). The BRs are considered as “learning laboratories for sustainable development” (Ishwaran et al. 2008), since they can be platforms for policies and practices that facilitate the emergence of knowledge-based management arrangements to demonstrate integrated and innovative approaches to conservation and sustainable development (Nguyen et al. 2011).

Given the multi-dimensional and dynamic nature of BRs, there is a clear need for a systemic approach in addressing this complexity (Hjorth and Bagheri 2006). System dynamic models (SDMs) provide a framework for managing changes, through the understanding of the dynamic interactions, delays and feedbacks embedded in complex systems (Rasmussen et al. 2012; Martínez-Fernández et al. 2013; Zhao and Zhong 2015).

Von Geibler et al. (2011) stated that the differentiation between sustainable and non-sustainable development requires the analysis of the interactions between indicators within a socio-ecological system. Nevertheless, these interactions cannot be addressed using traditional, static catalogues of indicators. The integration of sustainability indicators into a dynamic model system allows to assess how any variation in one indicator may lead to a series of responses in other indicators (Liu et al. 2014; Zhang et al. 2015).

The use of SDMs allows decision makers to anticipate the long-term consequences of their decisions and actions, as well as the unintended consequences and uncertainty of policies and strategies. For this purpose, scenario development is one of the major tools used to visualise and compare the potential outcomes of a variety of policies and to develop conservation strategies that are more resilient to global change. In this sense, the purpose of this work is to apply the Fuerteventura Biosphere Reserve sustainability model (FSM, Banos-González et al. 2013, 2015, Chapter 3 of this thesis) to assess the Fuerteventura Biosphere Reserve Action Plan (AP 2013), regarding proposed environmental sustainability goals, indicators and policy measures, as well as the internal coherence among all these features. It is assessed some key objectives of environmental sustainability of the Biosphere Reserve Action Plan (AP 2013), along with some measures which have been proposed to meet these objectives. A selection of environmental indicators was used, contained in the Action Plan and which are also part of the set of sustainability indicators integrated into the model. These indicators will help to assess the performance of different measures along the 2012-2025 period and to know whether the objectives of the AP would be met.

Therefore, this work tries to answer the following questions:

(1) How do the analysed indicators react under a set of environmental measures?

(2) What is the degree of uncertainty in the expected model response under the analysed measures?

(3) Do these environmental measures meet the objectives of the Biosphere Reserve Action Plan?

(4) How can thresholds and trade-offs assist the decision process?

4.2. METHODOLOGICAL APPROACH

4.2.1. The Fuerteventura socio-ecological system

The growth of tourism on the arid island of Fuerteventura has taken place later than on the other islands of the archipelago (Díaz et al. 2010). Nevertheless, tourism has already become the main driving force of the socio-economic and environmental changes on the island (Santana-Jiménez and Hernández 2011).

Due to these recent changes and the vulnerability of its ecosystems, Fuerteventura is considered a relevant case to drive the management and decision-making process towards more-sustainable development.

Regarding the environmental dimension, **Table 4.1** summarises the main strengths, weaknesses, opportunities and threats identified in the Biosphere Reserve.

Table 4.1. Matrix SWOT regarding the environmental dimension in Fuerteventura Biosphere Reserve.

STRENGTHS	WEAKNESSES
1. A unique location, with beaches of natural beauty and a relatively-stable political environment as advantages. 2. Fuerteventura is not a crowded destination (Santana and Hernandez 2011). 3. Ecosystem services derived from traditional agro-landscapes, such as “gavias” (Díaz et al. 2011).	1. Hyper-arid climate and water scarcity. 2. Soils show very low organic C concentrations, typical arid region with sparse vegetation and extremely-low biomass production, which represent a serious constraint to agricultural production (Tejedor et al. 2002). 3. Scarce contribution of renewable energy sources to the total energy. 4. Vulnerability of its ecosystems to climate change (Lloret and González-Mancebo 2011; Cropper and Hanna 2014).
OPPORTUNITIES	**THREATS**
1. Great potential to increase the renewable energy contribution. 2. Promotion of fodder production aimed at satisfying domestic demand. 3. Improvement of water management to maximise the water reuse.	1. Degradation of landscape and high-quality natural vegetation (Rodríguez-Rodríguez et al. 2005). 2. Abandonment of traditional activities (Dorta-Santos et al. 2014) 3. Dependence on fodder importation. 4. Rising dependence on external, non-renewable energy resources. 5. Rising concern about key species conservation.

4.2.2. Threats, targets and indicators of environmental sustainability

In order to address these threats, a set of 10 environmental sustainability indicators of the Fuerteventura Biosphere Reserve Action Plan, addressing the key environmental targets of this Plan, were selected and included in the FSM.

Table 4.2 shows these targets, the threats which they are intended to address and the 10 indicators used for their assessment. These indicators allow the analysis of the trends under different options along the 2012-2025 period. The formulation of the indicators may be consulted in **table 4.3**.

Table 4.2. Threats, the objectives intended to address them and the selected indicators used in the assessment of these objectives.

Threat number according to Table 1	Objectives	Selected indicators
1	To maintain the landscape and the high-quality natural vegetation.	High-quality vegetation proportion Overgrazing indicator Landscape indicator
2	To restore abandoned traditional agricultural areas.	Proportion of active gavias Landscape indicator
3	To minimise the dependence on fodder importation.	Fodder importation needs proportion Landscape indicator
4	To reduce the dependence on external, non-renewable energy resources.	Per capita primary energy consumption Renewable energy proportion Per capita CO_2 emissions
5	To conserve key species.	High-quality vegetation proportion Houbara habitat proportion Egyptian vulture population proportion.

Moreover, the most-attractive idea for numerous authors (Gallopin 1997; Moldan et al. 2012; Proelss and Houghton 2012) is to identify a reference value for sustainability, since a threshold gives the indicator meaning and quantifies what is acceptable regarding sustainability. Rickard et al. (2007) stated that a meaningful reference value may be a background value, standard or norm, or it can be a threshold value for something like the irreversibility of the socio-ecological system. When there were no published references for an indicator, a threshold based on a proportion of the value adopted for that indicator in 2009, when Fuerteventura was declared a Biosphere Reserve (UNESCO 2009) was established. This proportion, related to the concept of “Limit of Acceptable Change” (LAC, Stankey et al. 1985; Diedrich et al. 2011), is understood as the amount of change to be allowed to occur, since actions of conservation and development should coexist in areas such as the BRs (Price et al. 2010). In this work, 75% of the 2009 value was set as the LAC, since this proportion allows certain change due to socio-touristic dynamics, but the threshold is still far from compromising the conservation goals. It should be noted that this value of 75% refers to land outside the Protected Areas, since no land use changes occurred within them (**Table 4.4**).

Table 4.3. Model formulation of the 10 selected indicators collected in Table 4.2.

Indicators	Equations	Variables involved.
High quality vegetation proportion (hqp)	$hqp = \frac{hqv}{totv}$	hqv: high quality natural vegetation area. $totv$: total natural vegetation.
Landscape indicator (li)	$li = \left(\frac{hqv + gav}{bu + in} \right)$	hqv: the high quality vegetation area. gav: the area occupied by active gavias. bu: the urban built-up area. in: the area occupied by infrastructures (roads and tracks).
Overgrazing indicator (oi)	$oi = \left(\frac{ls \cdot ngp}{rf \cdot src} \right)$	ls: livestock of the island. ngp: net grazing proportion. rf: rainfall. src: sustainable stocking rate capacity.
Active gavias proportion (gap)	$gap = \frac{gav}{ga_{ref}}$	gav: the area occupied by active gavias. ga_{ref}: reference value for the area occupied by active gavias
Fodder importation needs proportion (fin)	$fin = \frac{trf - fg - fs}{trf}$	trf: total required fodder from cattle. fg: fodder consumed by grazing cattle (not imported). fs: fodder used for feeding the feedlot cattle.
Per capita primary energy consumption ($PEpc$)	$pe_{pc} = \frac{pep + pei + ped + pev + pen}{tpo}$	pep: urban primary energy consumed. pei: primary energy consumed in the industry sector. ped: primary energy consumed in the desalination processes. pev: primary energy consumed by the vehicles in the island. pen: primary energy consumed in the navigation sector (boats and flights). tpo: total population.
Share of renewable energy (SER)	$ser = \frac{wp + thp + php}{pep + pei + ped}$	wp, thp and php are the energy produced by renewable resources: wind power, thermal power and photovoltaic power, respectively pep, pei and ped are the primary energy demand from population (resident and tourist), productive activities and the seawater desalination, respectively.

Indicators	**Equations**	**Variables involved.**
Per capita CO_2 emissions (CO_2pc)	$c_{pc}=\frac{c_{elc}+c_{wst}+c_{nav}+c_{veh}+c_{gav}+c_{irr}+c_{gof}}{tpo}$	c_{elc}: CO_2 emissions from electricity consumption. c_{wst}: CO_2 emissions from urban waste production. c_{nav}: CO_2 emissions from navigation sector (boats and flights). c_{veh}: CO_2 emissions from the vehicles in the island. c_{gav}: CO_2 emissions from active gavias. c_{gav}: CO_2 emissions from irrigation. c_{gof}: CO_2 emissions from golf courses area. *tpo*: total population. ch_{ag}: annual changes in abandoned gavias area (from and to active gavias).
Houbara habitat proportion (*hhp*)	$hhp=\frac{(ch_{ag}\cdot HP_{ag})+(par\cdot HP_{pa})-(bu\cdot HP_{bu})-(nr\cdot HP_{nr})-(nt\cdot HP_{nt})}{hh_{ref}}$	HP_{ag} is the proportion of abandoned gavias which is part of the habitat. *par*: the abandoned gavias to natural vegetation succession rate. HP_{pa}: the proportion of natural vegetation which is part of the habitat. *bu*: the annual change of urban areas. HP_{bu}: the proportion of these urban areas which negatively affect the habitat. *nr* and *nt:* the new paved roads and unpaved tracks which annually appear on the island, respectively. HP_{nr} and HP_{nt}: the proportion of the new roads and tracks which negatively affect the habitat, respectively. hh_{ref}: reference value.
Egyptian vulture population proportion (*Evp*)	$Evp=\frac{\left(ev\cdot mir\cdot\frac{k+k_{ls}-ev}{k+k_{ls}}\right)-\left(\left(ep\cdot pli\cdot ev+f_{stk}\right)+pos\right)}{ev_{ref}}$	*ev:* population of the Egyptian vulture. *mir:* is the maximum or intrinsic growth ratio for the Egyptian vultures. *k*: Egyptian vulture carrying capacity without considering the livestock effect. k_{ls}: the additional carrying capacity generated by the existence of livestock. *ep*: the probability of electrocution. *pli*: the length of power lines on the island. f_{stk}: the stochastic factor included in the electrocution probability. *pos:* refers to poisonings. ev_{ref}: reference data of the population of the Egyptian vulture.

Table 4.4. Selected sustainability indicators. Units, direction of change and and thresholds are also specified.

Indicators	Units	Direction of change	Threshold	Meaning of the threshold	References of the thresholds
High quality vegetation proportion (*hqp*)	Dimensionless	More is better	LCA>0.1394	0.139 represents the LAC (75%) from the value in 2009.	Model value in 2009.
Landscape indicator (*li*)	Dimensionless	More is better	LCA>2.7345	2.74 represents the LAC (75%) from the value in 2009.	Model value in 2009.
Overgrazing indicator (*oi*)	Dimensionless	Less is better	<1	Values above 1 mean overgrazing.	Banos-González et al. (2015).
Active gavias proportion (*gap*)	Dimensionless	More is better	LCA>0.0915	0.092 represents the LAC (75%) from the value in 2009.	Perdomo-Molina. (2002)
Fodder importation needs proportion (*fin*)	Dimensionless	Less is better	LCA<0.7225	0.7225 represents the LAC (75%) from the value in 2009.	Model value in 2009.
Per capita primary energy consumption (*PEpc*)	GJ/ year*pc	Less is better	<42 GJ	Minimum energy use required to reach a Human Development Index of at least 0.8, recommended by United Nation Development Programme.	Johansson and Goldemberg (2004).
Share of renewable energy (*SER*)	%	More is better	>0.2	Renewable energy to represent at least 20% of total energy use in 2020 and 27% in 2030.	EC (2008, 2015).
Per capita CO_2 emissions (CO_2pc)	metric tones CO_2/ year*pc	Less is better	<9.52	A 20% reduction in the per capita CO_2 emissions from 1990 levels. Based on 1999 value (Duro and Padilla 2006).	EC (2008).
Houbara habitat proportion (*hhp*)	Dimensionless	More is better	LCA>0.75	0.75 is the Limit of Acceptable Change (75% of the 2009 value).	Model value in 2009.
Egyptian vulture population proportion (*Evp*)	Dimensionless	More is better	LCA>0.75	0.75 is the Limit of Acceptable Change (75% of the 2009 value).	Model value in 2009.

4.2.3. Sensitivity analysis

As pointed out by Ascough et al. (2008), Warmink et al. (2010) and Mosadeghi et al. (2013), uncertainty analysis is indispensable in modelling since it provides information on the uncertainties of the model. Frequently, the effects of uncertainty are not explicitly incorporated into model outputs, especially when socio-ecological models are concerned, largely due to time and other resource constraints (Kelly et al. 2013). However, the sensitivity analysis is of crucial importance when models are used to analyse policies, for which the uncertainties of model outcomes should be determined previously.

In this work, the most-sensitive parameters for each indicator (parameters showing a sensitivity index greater than 50%, **Equation 5.1**), by means of “Once factor at a time” sensitivity analysis were first identified (Holmes and Johnstone 2010; Sun et al. 2012; Moreau et al. 2013). For each indicator and for each parameter, a set of 200 simulations was performed along the parameter range. The sensitivity index at time *t* was computed following the equation suggested by Jørgensen and Fath (2011) (see **Chapter 5** for details).

Once the most sensitive parameters for the selected indicators haved been determined, the Monte Carlo sensitivity analysis (MC) simulation was carried out, with a Latin Hypercube sampling (Hekimoğlu and Barlas 2010). The MC simulations generated the confidence intervals of the model output for the selected indicators. In this work, a total of 10 MC simulations –one per indicator- were run. Each MC simulation consisted of 200 model runs in which the values of the most-sensitive parameters ($S_{i,j}$ >50%) were changed randomly along their respective parameter ranges (Arabi et al. 2007; Makler-Pick et al. 2011). These ranges were determined according to several sources of information (mainly local experts, institutional reports, statistics and scientific literature). In the cases where these reasonable ranges could not be established, variation of ± 25% was applied (Ford 1990).

4.2.4. Descriptions of the measures

Since the general purpose of this work is to assess the Fuerteventura Biosphere Reserve Action Plan (AP 2013), the following proposed measures in the AP, intended to remove the identified endogenous threats (**Table 4.1**), were defined and implemented into the FSM. In order to simulate each policy measure, the model structure was expanded to include all necessary new variables, parameters and relationships. This required to perform an additional stage of model building, from data gathering to model formulation.

M.1) ***100% renewable water***

As mentioned in Table 1, the consumption of desalinated water represents one of the key issues for the Biosphere Reserve, due to the rising consumption of electrical energy in the supply of this basic resource.

To address objective 4 (**Table 4.2**), the aim of this measure is to cover 100% of the electricity demand required for the supply of desalinated water with renewable energy in 2025; as such, it represents one of the basic guidelines of the Biosphere Reserve (AP 2013 and per. com). In line with this, a pilot project was carried out in 2010 on the island: the construction of a 1.7 Mwh wind farm to provide electricity for internal consumption, associated with a seawater desalination plant with the capacity to produce 4,000 m^3 of water per day (Renforus 2014), which represents around 8% of the desalinated water produced in 2012.

M.2) ***Reduction of the grazing pressure***

The Action Plan considers this measure as a specific objective in order to protect the soil and the high-quality natural vegetation (Objective 1, **Table 4.2**), such as Tabaiba scrub (dominated by species of the genus *Euphorbia*) and the endemic scrub (*Euphorbietum handiensis*) (Rodríguez-Rodríguez et al. 2005; del Arco et al. 2010). At the same time, cattle breeding constitutes one of the traditional economic activities of the island which must be preserved. Moreover, cattle are a key factor affecting the population of one of the flagship species: the Egyptian vulture (Mateo-Tomás and Olea 2015).

In this chapter, two options based on the proportion of food that cattle obtain by grazing (net grazing proportion or NGP) were analysed:

(M.2.1) This measure considers that the NGP is reduced from 50% under Business as Usual (BAU) to 29%, the minimum value in Fuerteventura according to the literature (Mata et al. 2000).

(M.2.2) The NGP falls to 10%.

M.3) *Restoration of abandoned fields (gavias)*

This option, promoted by the island council (Fuerteventura Cabildo 2009), consists of reusing urban reclaimed water (from the resident population) to restore abandoned fields (gavias) and thus enhance the landscape indicator (Díaz et al. 2011). This measure can contribute to two different additional goals, depending on the final use of the crops:

(M.3.1) The reduction of fodder importation needs. This measure was based on open interviews with farmers and decision-makers on the island. They communicated the need to reduce the dependence on fodder importation, by cultivating fodder in restored gavias. Moreover, some authors (Palacios et al. 2008) underlined the suitability of the use of reclaimed water resources (RW) to cultivate fodder species such as alfalfa (Medicago sativa) and sudangrass hybrid (Sorghum bicolor ssp. sudanense). This measure would address objectives 2 and 3 (**Table 4.2**).

(M.3.2) The reduction of grazing pressure on high-quality natural vegetation. The fodder cultivated in newly-restored gavias would feed the grazing cattle, which could be removed from the high-quality vegetation areas, in line with objectives 1 and 2.

M.4) Restoration of abandoned fields (gavias) using desalinated water

The high volume of water required for fodder crop production highlights the need for an alternative source of water for irrigation, in addition to the reclaimed water. Therefore, this measure consists of obtaining the water required for fodder production in the form of desalinated water. As in the previous measure, two possible options were studied: i) Reduction of fodder importation needs due to an increase in fodder production on the island for enclosed cattle (M.4.1) and ii) Cultivation of fodder on the restored gavias to reduce the grazing pressure on high-quality natural vegetation (M.4.2).

M.5) Integration of measures 1 and 4: gavias restoration with desalinated water from renewable energy

In order to advance in sustainability and to be coherent with the project that aims to make the water used 100% renewable, this measure envisages the production of desalinated water - for the irrigation of fodder crops on the island – by using renewable sources of energy.

Since the effect of applying measure 1 on the measure 4 would only affect the three indicators directly related to energy issues (*PEpc*, *SER* and CO_2pc) and they barely vary among M.4.1 and M.4.2, the measure 5 represents the combination of measure 1 and one of the options of M.4, in this case, M.4.1.

This option, M.5, would allow objectives 2, 3 and 4 to be addressed.

4.3. RESULTS

Table 4.5 shows the simulation results for the main indicators regarding these measures, as well as under BAU simulation. The estimated uncertainty for the expected results is also expressed, as 95% confidence intervals around each simulated value, according to the MC analysis.

4.3.1. Uncertainty analysis

Table 4.5 presents the results of the MC simulations, with the expected uncertainty (variation coefficient respect to the average value using 95% confidence interval) of each indicator under each measure simulation.

Almost all the indicators have an average uncertainty of between 15 and 40%, except *gav* and *fin*, with very-low uncertainty, and *hqp*, with an uncertainty of 79.55% around its average value (**Fig. 4.1**).

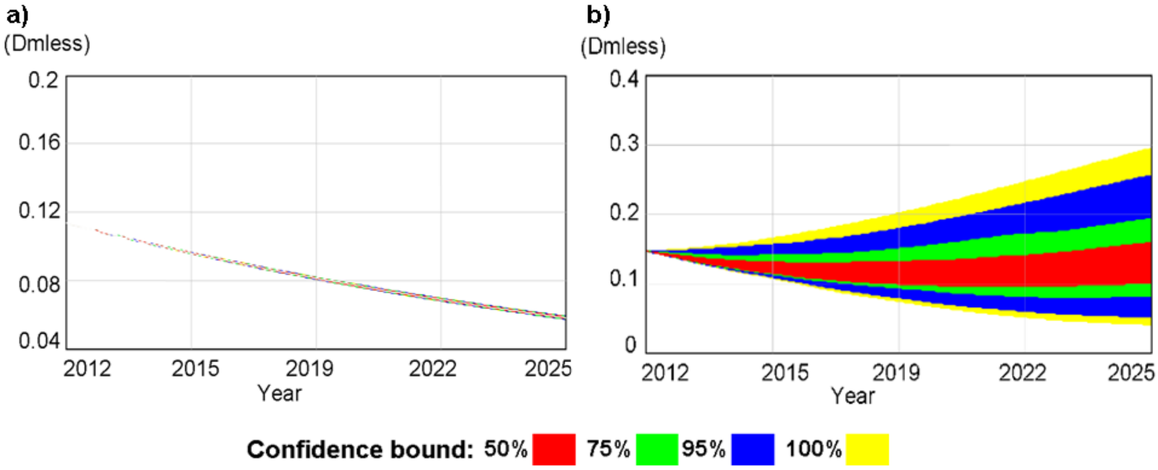

Figure 4.1. Monte Carlo sensitivity analysis simulations under BAU showing the indicators with minimum, a) gavias proportion, and maximun, b) high-quality vegetation, uncertainty.

4.3.2. Measures analysis

4.3.2.1. 100% renewable (M1)

The results under BAU show that the urban demand for desalinated water would double between 2012 and 2025 due to the increase in population (both resident and tourist equivalent). The same increase would be expected for the electrical energy consumption, which would reach 4,564 ± 1,613 GJ/year between 2012 and 2025. The total primary energy consumption would also increase, by around 52% (to 29,174.4 ± 9,994 GJ/year in 2025), whereas the expected rise of the share of renewable power production (*SER*) on the island would be around 14% under BAU.

However, indicators such as the per capita primary energy consumption (*PEpc*) and the per capita CO_2 emissions (CO_2pc) would improve between 2012 and 2025, despite the increases in the overall consumption and emissions, respectively (**Table 4.5**).

Under measure 1 -all the power demand of desalination processes was provided by renewable power- the *SER* would increase by around 52%, although its impact on the total power energy system would be rather small. Likewise, the CO_2pc would be reduced by around 7.5% under BAU.

4.3.2.2. Reduction of the grazing pressure (M2)

Under the BAU simulation, the proportion of high-quality natural vegetation (*hqp*) and the landscape indicator (*li*) would be reduced by around 10% and 76%, respectively, between 2012 and 2025. In the latter case, this noticeable decrease would be caused by increases in the urban uses and infrastructures, due to urban sprawl. The overgrazing indicator (*oi*) would reach values close to 0.7 ± 0.17, meaning an increase in almost 4% along this period.

Under the measures which aim to reduce grazing, an improvement of these indicators would be achieved. For example, the loss of the *hqp* would be reduced by around 13.5% in 2025 under both measures (M.2.1 and M.2.2), compared to BAU, meaning a change in the trend of this indicator: from a loss to a recovery. The same pattern would be followed by the *li*, which would undergo an improvement double that under BAU. Regarding the *oi*, the M.2.1 would mean a reduction of around 26.6%; whereas, under a more-restrictive measure, M.2.2, the reduction would be around 75%.

Nevertheless, the reduction in the grazing proportion considered under M.2.1 would lead to a decrease of 24.8% in the proportion of Egyptian vultures (*Evp*), since the grazing cattle form the basis of their diet, whereas this indicator would show a trend to increase between 2012 and 2025 under BAU. The reduction of *Evp* would reach almost 75% in 2025 under M.2.2.

The reduction in the grazing proportion implies an additional increase in fodder consumption, compared to BAU. Based on the estimated increase in around 27.5% in the fodder requirements of the cattle on the island between 2012 and 2025 under BAU, fodder importation needs (*fin*) would additionally increase by 16% and 45% under M.2.1 and M.2.2 respectively, as compared to the BAU.

Table 4.5. Simulation results for the 10 indicators under BAU and the analysed measures.

Indicator	*hqp*	*li*	*oi*	*gap*	*fin*	*PEpc*	*SER*	*CO_2pc*	*hhp*	*Evp*
Threshold	**>0.139**	**>2.735**	**<1**	**>0.092**	**<0.722**	**<42 GJ**	**>0.2**	**<9.52**	**>0.75**	**>0.75**
BAU	0.132	0.594	0.679	0.058	0.587	281.966	0.011	17.04	0.765	1.269
	± 0.111	± 0.258	± 0.166	± 0.001	± 0.086	± 42.073	± 0.004	± 4.21	± 0.108	± 0.363
M 1	0.132	0.594	0.679	0.058	0.587	275.731	0.017	16.89	0.765	1.269
	± 0.111	± 0.258	± 0.166	± 0.001	± 0.086	± 2.174	± 0.003	± 4.21	± 0.108	± 0.363
M 2.1	0.150	1.303	0.498	0.058	0.681	281.966	0.011	17.04	0.765	0.954
	± 0.114	± 0.45	± 0.012	± 0.001	± 0.002	± 42.073	± 0.004	± 4.21	± 0.108	± 0.124
M 2.2	0.150	1.303	0.172	0.058	0.852	281.966	0.011	17.04	0.765	0.383
	± 0.114	± 0.45	± 0.004	± 0.001	± 0.003	± 42.073	± 0.004	± 4.21	± 0.108	± 0.043
M 3.1	0.132	0.610	0.680	0.148	0.498	280.944	0.011	16.95	0.755	1.269
	± 0.111	± 0.250	± 0.166	± 0.002	± 0.085	± 42.112	± 0.004	± 4.19	± 0.114	± 0.363
M 3.2	0.147	1.125	0.565	0.148	0.556	280.944	0.011	16.95	0.755	1.076
	± 0.109	± 0.345	± 0.138	± 0.002	± 0.07	± 42.112	± 0.004	± 4.19	± 0.114	± 0.305
M 4.1	0.131	0.67	0.687	0.405	0.114	296.157	0.011	17.16	0.72	1.269
	± 0.111	± 0.282	± 0.166	± 0.001	± 0.007	± 52.459	± 0.003	± 4.16	± 0.026	± 0.363
M 4.2	0.150	1.504	0.069	0.733	0.172	315.91	0.01	17.46	0.675	0.185
	± 0.108	± 0.514	± 0.021	± 0.001	± 0.025	± 62.024	± 0.003	± 4.12	± 0.108	± 0.055
M 5	0.131	0.67	0.687	0.405	0.114	272.228	0.033	16.6	0.72	1.269
	± 0.111	± 0.282	± 0.166	± 0.001	± 0.007	± 40.734	± 0.011	± 4.12	± 0.026	± 0.363

4.3.2.3. Restoration of abandoned fields (gavias) (M3)

Under the BAU simulation, active gavias would be reduced by nearly a half, from 434.73 to 220.89 ± 3.36 ha, due to crop abandonment.

Under M.3, the gavias proportion (*gap*) would increase by 54%, relative to BAU, between 2012 and 2025. This restoration would affect the habitat of the houbara, since abandoned gavias represent part of its habitat (Carrascal et al. 2008). Under the BAU scenario, the proportion of houbara habitat (*hhp*) would decrease by 17.7% due to urban sprawl and the increasing demand for paved roads and tracks. The restoration of abandoned gavias would mean a slight additional loss of 1.32% in the houbara habitat, respect to BAU.

Under M.3.1 (cultivation of fodder in restored gavias to reduce the importation needs), the *li* would improve by almost 3% relative to BAU. The *oi* would worsen, reaching values around 0.68 ± 0.17. Regarding the *fin*, a reduction of around 5% would be achieved under M.3.1, in comparison to BAU, whereas this reduction would reach around 15% under P.3.2.

If restored gavias were used to grow fodder to reduce the grazing pressure on the high-quality vegetation (M.3.2), the *hqp* and *li* would improve by around 11% and 90%, respectively, relative to BAU, and *oi* would fall by around 17%. Nevertheless, the Egyptian vulture proportion would decrease by around 15%, compared to BAU.

4.3.2.4. Restoration of abandoned fields (gavias) using desalinated water (M4)

If all the fodder required for cattle consumption was grown on the island, 1,539 ha would need to be farmed for this purpose. In 2012, there were more than 3,200 ha of gavias (both active and abandoned), so the restoration of abandoned gavias and their cultivation seem plausible. However, there is still a limiting factor: water for irrigation.

As seen above, the use of RW would not be enough, due to the high volume of water required for the fodder crop production. The fodder production under M.3.1 would only supply around 15% of the total fodder importation needs. Therefore, a more-ambitious option would need to be set up on the island. This option (M.4.1) would consist of obtaining the additional volume of water required as desalinated water. Under this measure, the proportion of active gavias would be around five times than under BAU. This would mean an 80% reduction in the fodder importation needs.

However, since abandoned gavias would be restored, the values of some indicators would worsen. The *oi* and the *hqp* would slightly worsen, by around 1.17% and 0.83%, respectively. The *hhp* would also suffer an additional loss of around 6%.

This change in the importation needs should decrease the CO_2pc, due to the reduction of ocean transportation of imported fodder and the increase in CO_2 sequestration by crops in gavias. However, the expected improvements would remain hidden by the increase in around 60% in the energy demands associated with the seawater desalination processes. In fact, the CO_2pc and *PEpc* would increase under M.4.2 by around 0.7% and 5%, respectively.

If the increase in fodder production on the island with the use of desalinated water was aimed at reducing the cattle pressure on high-quality natural vegetation (M.4.2), some important changes in the indicators would be expected. The *gap* would be boosted more than 10-fold relative to BAU. This means that around 2,783 ± 4 ha would be needed to cultivate the fodder required by the cattle in 2025. The *oi* would decline by around 90% and the *hqp* would increase by around 14%. This measure would also allow a reduction of the *fin* of around 70%, compared to BAU.

As under M.4.1, the CO_2pc and *PEpc* would increase by around 2.5% and 12%, respectively. Likewise, the *hhp* would suffer an additional loss of approximately 12%. Furthermore, the important reduction in grazing cattle under M.4.2 would reduce the *Evp* by around 85%.

4.3.2.5. Integration of measures 1 and 4: gavias restoration with desalinated water from renewable energy (M5)

If M.1 and M.4.1 were implemented jointly, the energy consumption from non-renewable sources would be reduced by around 8% and 30%, relative to BAU and M.4.1, respectively. This would mean an important increase in the proportion of renewable energy, *SER*, around 84% compared to BAU.

The reduction of CO_2 emissions associated with fodder importation, added to the increase in the CO_2 absorption by active gavias, would lead to a reduction in the net annual emissions: around 2.6% and 3.3% compared with BAU and M.4.1, respectively.

4.4. DISCUSSION

As question 1, "*How do the indicators analysed react under a set of environmental measures?*", has been extensively answered in the previous section, in the discussion the other questions outlined in the Introduction will be addressed.

4.4.1. What is the degree of uncertainty in the expected model response under the analysed measures?

Kelly et al. (2013) stated that for management models, such as FSM, the final users may be more concerned with being able to estimate the magnitude of the effects of different policy options rather than precise values. However, an uncertainty analysis is necessary to estimate the precision ranges of the expected results and avoid misunderstandings in the interpretation of model outcomes. Overall, the uncertainty analysis shows that the expected outcomes under the measures analysed have a low-to-moderate degree of uncertainty; therefore, the results obtained are relevant to the decision-making process (Schouten et al. 2014; Song et al. 2015). Nevertheless, the results in **Table 4.5** mean that decision-makers should take with caution the measures involving indicators with a high uncertainty, which is particularly the case for the high-quality natural vegetation proportion. More generally, the precautionary principle should be applied to the uncertainty analysis: so, the higher the uncertainty, the less risky the policy should be.

Some authors state that the precautionary principle should not represent a brake to decision-making, since inaction could have costly and unforeseeable impacts (Gee and Krayer von Krauss 2005; Van der Sluijs 2007). However, uncertainty should be considered a normal component of decisions and, instead of inaction, it should appeal to the prudence of policy makers.

4.4.2. Do these environmental measures meet the objectives of the Biosphere Reserve Action Plan?

Regarding objective 1, which aims to maintain the landscape and the high-quality natural vegetation, only those measures aimed at reducing the grazing pressure (M.2.1, M.2.2, M.3.2 and M.4.2) would improve the values of the indicators involved in this objective: the high-quality vegetation proportion (*hqp*), overgrazing indicator (*oi*) and landscape indicator (*li*). Measure 1 would not affect this objective. Measures 3.1, 4.1 and 5 would worsen these indicators, making the objective more difficult to achieve, in line with the authors who consider that overgrazing causes vegetation degradation (Nogales et al. 2006; del Arco et al. 2010; Garzón-Machado et al. 2010). The FSM supports this relationship and allows for the quantification of the effect of overgrazing on the high-quality vegetation.

The restoration of abandoned traditional agricultural areas, the focus of objective 2, would remain constant or improve under the analysed measures. The biggest improvement would occur under M.4.2, since a large amount of fodder would be cropped in restored gavias. Some authors (Dorta-Santos et al. 2014) and stakeholders (pers. com) agree on the importance of the maintenance of active gavias as a traditional agro-system which contributes positively to the scenic quality of the landscape. Moreover, their morphology favours the soil content of organic nutrients and water, contributing to the natural fertilisation of the crops and the aquifer recharge (Hernández-Moreno et al. 2007; Díaz et al. 2011).

Concerning objective 3, which aims to minimise the dependence on fodder importation, the stock-breeders generally advocate a reduction in the importation of fodder in favour of its cropping on the island, which would mean the restoration of certain abandoned gavias (pers. com). The reduction of grazing considered under M.2.1 and M.2.2 would require an increase in the importation of fodder whereas the remaining measures would reduce it. The maximum reduction (around 80%) would be achieved under M.4.1 and M.5. However, there is a trend on the island towards an increasing number of cattle herds which, to some extent, would decrease the effectiveness of these measures regarding fodder importation.

Since the increase in fodder crops would be possible due to the restoration of abandoned fields, other indicators such as *gap* and *li* would improve too.

In relation to objective 4, the reduction of the dependence on non-renewable energy resources, measures 1 and 5 would yield better results than BAU for the indicators per capita primary energy consumption (*PEpc*), per capita CO_2 emissions (CO_2pc) and the share of renewable energy (*SER*). Nevertheless, even under these measures, the advances achieved would be minimal, since they only include partial actions. More-specific and ambitious measures and policies are needed, particularly in insular systems, whose transport usually is extremely dependent on fossil fuels (Becken 2002; Becken et al. 2003; Kuo and Chen 2009).

Regarding objective 5, the conservation of key species, the effects of each measure on the *hqp* have been mentioned previously. However, the other two indicators suggested in **table 4.2**, the Egyptian vulture population proportion (*Evp*) and the houbara habitat proportion (*hhp*), are not addressed by any specific measure.

Although the Canarian houbara is not considered a good surrogate for certain aspects of biodiversity, such as species richness (Carrascal et al. 2012), it is a keystone species with regard to raising awareness of more-general conservation needs and may also encapsulate the needs of other species on steppe areas and in arid environments (Le Cuziat et al. 2005; Palomino et al. 2008). Loss of habitat seems to be the main factor threatening the houbara population in Fuerteventura (Lorenzo 2004; Carrascal et al. 2008). The results of modelling show that land uptake and infrastructures are the factors contributing most to the habitat loss. However, the restoration of abandoned gavias, considered under the options M.3, M.4 and M.5, would mean a reduction of *hhp*, with an additional loss of 12% under M.4.2, with respect to BAU.

The *Evp* would be affected by the measures aimed at reducing the grazing, since livestock increase the island's carrying capacity to host this scavenger (Mateo-Tomás and Olea 2015). Under M.2.1, M.2.2 and M.4.2, the reduction of this indicator would be around 25%, 70% and 85%, respectively, compared to BAU. This situation would suppose a clear threat to this endangered species that managers should avoid.

Although the Action Plan considers some specific measures to preserve flagship animal species, such as controlling predators or poisons, our assessment highlights the importance of the indirect effects of other environmental measures and the need to apply an integrated analysis.

In synthesis, although neither of these measures addresses objective 5 (biodiversity conservation) and, therefore, no advances within this objective would be expected, some achievements would be reached regarding objectives 1, 2, 3 and 4. Nevertheless, none of these measures would allow the improvement of all the analysed indicators. Their integration in the FSM allows to visualise and quantify the negative effects that certain measures could have on other indicators. These might go unnoticed if only a set of static indicators was used. Therefore, the assessment of the potential trade-offs among objectives is essential.

4.4.3. How can thresholds and trade-offs assist the decision-making process?

As mentioned, these analyses support the existence of some trade-offs between environmental objectives, in which the optimisation of some indicators implies the worsening of others (MEA 2005; Rodríguez et al. 2006). Many authors underline the need to take into account the trade-offs in the decision-making process (Su et al. 2012;

Moeller et al. 2013; Vidal-Legaz et al. 2013). In the subsequent paragraphs, the discussion is focused on how the indicators behave regarding their thresholds and which trade-offs are identified, in order to prioritise among the measures analysed.

According to Rodríguez-Rodríguez and Martínez-Vega (2012), the establishment of thresholds for every indicator is a clear step forward in sustainability since they represent a reference for decisions in terms of sustainability and allow to define acceptable ranges of change. As shown in **Table 4.5**, 4 out the 10 considered indicators would systematically exceed their thresholds under all the analysed measures. In the case of the landscape indicator, its decreasing trend is highly dependent on land use changes due to socio-touristic dynamics, which are not addressed in this chapter since such policies are not considered in the AP.

The other three indicators which would also exceed their thresholds under all the considered measures are *PEpc*, *SER* and CO_2pc, even though measures 1 and 5 explicitly address the improvement of such indicators. Under these options, the values remain very far from their thresholds (**Table 4.4**). While they achieve some degree of improvement, measures 1 and 5 are partial and clearly insufficient to fit the general objectives set out regarding the energy and climate change European policies (EC 2015).

From this point on, the analysis is focused on the six indicators that show different patterns under the measures proposed (and which would not be systematically above their thresholds). Following the rule: "*Threshold out, measure out*", if, under any option, the threshold of one of these six indicators is exceeded (**Table 4.5**), the measure should be rejected. This is in line with those who claim that actions that may lead to a risk should be avoided to prevent degradation of the resources and environment (González-Laxe 2005; Sampaio et al. 2015).

As shown in **Table 4.5**, M.1, M.2.1, M.2.2, M.3.1, M.4.1, M.4.2 and M.5 would lead to at least one of the six thresholds being exceeded. Therefore, applying the "*Threshold out, measure out"* rule, the adoption of these measures should be avoided. Only M.3.2, aimed at reusing urban reclaimed water to restore gavias and feed grazing cattle with the fodder cropped therein, would lead to none of the established thresholds being exceeded. Thus, it might be assigned the highest priority among the analysed measures.

Nevertheless, certain negative effects related to objective 5 could be expected under measure M.3.2. The indicators *hhp* and *Evp* would worsen by around 1.3% and 15%, respectively, relative to BAU. In order to compensate the identified trade-offs, some corrective measures should be incorporated into M.3.2. For instance, the loss of the secondary habitat of the houbara as a consequence of the gavias restoration might be compensated by land planning options that reduce new urban developments and infrastructures in its primary habitat (Young et al. 2005; Illera et al. 2010). Moreover, although not assessed in this work, the disturbances and the reduction in breeding success due to the presence of a high livestock density as well as the potential mortality of chicks caused by trampling (Lavee 1985) could be reduced by limiting grazing in sensitive areas which represent the habitat of the houbara (Garzón-Machado et al. 2010; Schuster et al. 2012). Regarding the Egyptian vulture proportion, the creation of 'vulture restaurants' may reduce the dependence of these scavengers on extensive livestock exploitations (Donázar et al. 2002; Gangoso et al. 2006) and thus minimise the negative effects caused by the reduction of grazing.

Beyond the incorporation of compensation actions to minimise trade-offs within any of these measures, it should be highlighted that the assessed measures, derived from the BR Action Plan, are insufficient to address objectives 4 (energy) and 1 (landscape conservation). Regarding objective 4, even measure 3.2 would result in the values of the indicators still being far from the thresholds (**Table 4.4**). This means that the overall goals set out by European Energy policies (EC 2015) will not be met. More-ambitious measures should be adopted regarding energy, as has occurred on other islands such as the neighboring El Hierro (Iglesias and Carvallo 2011), the Greek Dodecanese (Oikonomou et al. 2009) or the Danish Samsø (Nielsen and Jørgensen 2015).

In relation to landscape conservation issues, closely dependent on land use changes, there are no specific policies aimed at controlling the key driver: the development of tourism (Santana-Jiménez and Hernández 2011). Beyond the protected areas, the Action Plan does not explicitly address the limitation of land use changes in areas covered by high-quality vegetation. In line with the European Landscape Convention (Council of Europe, 2000), this kind of measure needs to be incorporated into the management plans (De Aranzabal et al. 2008).

Finally, it should be pointed out that relative indicators such as the per capita indicators *PEpc* and CO_2pc would improve in all the simulations, including BAU, between years 2012 and 2025, despite the rises in the consumption of resources and emissions in absolute terms. This is due to the even-higher increase in the total population along that period. Obviously, this does not imply that if more tourists come to the island, more sustainable the Fuerteventura Biosphere Reserve will be. Some relative indicators, particularly many efficiency indicators, do not always give sound information about sustainability when considered alone. These efficiency indicators and their changes along time should be taken with caution (Hanley et al. 2009), to avoid misunderstandings and errors in the diagnosis (Figge and Hahn 2004; Mori and Christodoulou 2012).

The analysis of the measures presented here has some shortcomings, particularly the lack of a cost-benefit analysis of the measures and an assessment of the main findings by policy makers and stakeholders. These tasks will be addressed in subsequent work. However, the work presented here illustrates how the integration of sustainability indicators and their thresholds into dynamic system models can be useful for quantitative sustainability assessments in Biosphere Reserves.

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CHAPTER 5

Application of sensitivity analysis on socio-ecological models

5. APPLICATION OF SENSITIVITY ANALYSIS ON SOCIO-ECOLOGICAL MODELS (FROM MODEL DEVELOPMENT TO THE ASSESSMENT OF MANAGEMENT DECISIONS)

Abstract

The assessment of socio-ecological system generally suffers from high levels of uncertainty. Its analysis is essential in modelling to provide decision-makers a realistic picture of the possible model outcomes. In this work, an extensive sensitivity analysis (SA) was applied in different stages of a dynamic model development and application: the Fuerteventura sustainability model.

The SA allowed: i) The improvement of model formulation, by removing the least sensitive parameters, using screening techniques such as One factor at a time (OAT). ii) A detailed assessment of robustness, by means of Monte Carlo simulations. These results showed a moderate response of the model outputs to changes in parameters values. iii) The identification of leverage points, by means of OAT, and their application to define management measures. Results suggest that measures based on leverage points are more effective than others proposed so far by different agents. iv) To show the importance of taking into account the uncertainty in the assessment of policies. Monte Carlo results show several examples in which the simulation results within 95% confidence bound might exceed the thresholds of some sustainability indicators under analysis, whereas the mean values would not. Therefore, the overcome of some thresholds might go unnoticed if uncertainties are not considered. v) The analysis of how uncertainty affects the assessment of the vulnerability of the system to some external drivers such as economic and climate change scenarios. Furthermore, the MC simulation results for the analysed indicators until 2025 suggest that Fuerteventura socio-ecological system is more reactive to policy intervention than to economic external drivers. This underlines the responsibility of decision-makers to address measures to contribute to a more balanced and sustainable development for the Fuerteventura socio-ecological system. Regarding the considered climate change scenarios (A2 and B2), MC results, although preliminary, point to the vulnerability of the Fuerteventura socio-ecological system to the ongoing climate change.

Key words: uncertainty; system dynamic models; policy assessment; vulnerability; leverage point

5.1. INTRODUCTION

5.1.1. Uncertainty in the assessment of socio-ecological systems

The analysis of socio-ecological systems should be tackled from a holistic, systemic perspective that enables an integrated assessment of socioeconomic and ecological factors and the nonlinear interactions and feedbacks of complex socio-ecological systems (Hodbod and Adger 2014; Lozoya et al. 2014). The application of the system dynamic modelling approach (Forrester 1961; Sterman 2000; Xu et al. 2015) have numerous advantages in the assessment of socio-ecological systems (SES), due to its capacity to conceptualize their complex interrelations and to facilitate their comprehension and monitorization (Kelly et al. 2013; Martínez-Moyano and Richardson, 2013) aimed at generating useful information for decision-making (Voinov and Shugart 2013; Liu et al. 2015).

Nevertheless, integral assessment of SES generally suffers from high levels of uncertainty (Nossent et al. 2011; de Rigo et al. 2013; Moreau et al. 2013; Verburg et al. 2013; Ropero et al. 2014). Uncertainty, as Hou et al. (2013) stated, represents “an analytical state of limited knowledge which aggravates the exact depiction of a system's current situation or the future outcomes of the system's development”. Complex environmental models are usually controlled by a high number of parameters, which may constitute a problem in their application, as the parameter estimation becomes a high-dimensional and mostly non-linear problem (Nossent et al. 2011). Nonetheless, the level of testing required to develop this understanding is rarely carried out, largely due to time and other resource constraints (Chu-Agor et al. 2012; Kelly et al. 2013).

For several authors (Ascough et al. 2008; Warmink et al. 2010; Mosadeghi et al. 2013), uncertainty analysis is indispensable in modelling since it illuminates the adequacy of models and reveals the reliability of the model outputs. Scenario analysis could be a tool to deal explicitly with different assumptions about the future, which is inherently uncertain (Refsgaard et al. 2007; Holzkämper et al. 2015). Likewise, it could be useful to assess the vulnerability of the system to future changes, which necessarily must be included in the decision-making process (Nelson et al. 2010).

In addition to the mentioned purposes of uncertainty analysis, Brown et al. (2005) and Jakeman and Letcher (2003) highlighted the importance of discovering policy leverage opportunities; it means “regions in parameters space where policy interventions may be particularly efficient”.

A review of recent published literature relevant to “uncertainty” arising from the analysis of social-ecological systems, has been carried out in order to explore the following issues:

- What does uncertainty mean in developing any model?
- Which sources of uncertainty are relevant for management?
- How can be these uncertainties in the assessment of socio-ecological systems delt with?

In relation to the first question, the concept of uncertainty has attracted many efforts especially in the field of philosophy of science (Halpern 2003; Mosadeghi et al. 2013). In addition to the aforementioned definition of Hou et al. (2013), others authors have synthesised uncertainty as “incomplete information about a particular subject” (Ascough et al. 2008; Yakomizo et al. 2014; Uusitalo et al. 2015). Natural environments, human behaviours and social dynamics remain subject to stochastic uncertainty inherent in these systems, which cannot be eliminated (Chang et al. 1993; Oreskes et al. 1994; Harremoës and Madsen 1999; Walker et al. 2003; Refsgaard et al. 2007; Warmink et al. 2010). Li and Wu (2006) described uncertainty as the inadequacy of people's knowledge to understand the system under investigation, and Breckling and Dong (2000) stated that a subject is uncertain when it is either not exactly known or determined or reliably foreseen. Following Oreja-Rodríguez et al. (2008), environmental uncertainty may be perceived as the lack of information about facts external to the organisation experienced by the individual according to their mental schemata, and depends on the dynamism and complexity of the most relevant items of the environment.

Uncertainty is an important consideration in developing any model, but it is particularly important and usually difficult to deal with in the case of complex systems models (de Rigo et al. 2013; Kelly et al. 2013; Ropero et al. 2014). As model complexity increases in order to better represent socio-ecological systems, there is a need to identify potential sources of uncertainty and to quantify their impact, so the appropriate management options can be identified with confidence (Ascough et al. 2008; Holzkämper et al. 2015).

Regarding question 2, Refsgaard et al. (2007) and Warmink et al. (2010), following Walker et al. (2003), described five possible locations of uncertainty: (i) context uncertainty, (ii) input uncertainty, (iii) model uncertainty, which consists of model structure uncertainty and model technical uncertainty, (iv) parameter uncertainty, and (v) uncertainty in the model outcomes. Verburg et al. (2013) stated that the major uncertainties in large-scale environmental assessments are a result of our incomplete knowledge and data of the SES, strong simplifications in model representations and the inherent uncertainty of socio-economic and political developments. Since often it is generalised and categorised into a limited number of aspects for analysis, inevitably certain information is lost in the development of the model. These structural errors constitute the basic uncertainty of models, particularly evident in tourist socio-ecological systems.

Focusing on the eminently tourist socio-ecological systems, Xing and Dangerfield (2011) found a significant amount of uncertainty, nonlinear changes and attitudinal data involved in fully understanding the forces behind tourism development. In this sense, Gössling and Hall (2006) and von Bergner and Lohmann (2013) stated that tourism is greatly influenced by external drivers, which include economic, environmental, political, social, and technological dimensions, which provide a high degree of uncertainty. Hou et al. (2013) emphasised the raise of uncertainties when the human dimension and all decision-based insecurities of societal and psychological processes are included in the analysis. These authors found "an overwhelming variety of insecurity correlated with landscape management" such as globalization, demographic change and migration, climate change, strategies for sustainable provision of energy or motivations for conservation of natural resources and ecosystem services.

All of these mentioned sources of uncertainty may be identified in our case of study. Moreover, since this is an integral assessment aimed at supporting the decision-making process, the importance of uncertainty in this process is widely recognised. Mosadeghi et al. (2013) claimed the need for explicit and systematic consideration of all potential uncertainties to develop an effective solution supported by the majority of stakeholders. Since policy makers make their decisions based on the available information, the evaluation and minimisation of uncertainties to avoid bias or even fault in decision making are crucial (Hou et al. 2013). Sohl and Claggett (2013) recommended the policy-makers to adopt a more rigorous viewpoint about uncertainty to be considered in the decision-making process and that the information provided by scientific advisors, must adequately communicate uncertainties.

Among the methods across literature which allow to cope with uncertainties in assessment of socio-ecological systems, the followings are highlighted: i) S*ensitivity Analysis* (SA), used to assess the contribution of parameters and inputs on model outputs and to identify key input variables and parameters that control model outputs (Schouten et al. 2014). An overview of SA methodologies can be found in Saltelli et al. (2005) and Cariboni et al. (2007). ii) *Monte Carlo Analysis (MC)*, a statistical technique for stochastic model calculations and analysis of error propagation in calculations. Its purpose is to trace out the structure of the distributions of the model output (Refsgaard et al. 2007).

Despite of the wide acknowledgment about the importance of uncertainty analysis for improving the understanding and the confidence on models use, a profound analysis is still infrequent, above all in relation to complex socio-ecological systems (Chu-Agor et al. 2012; Kelly et al. 2013). **Table 5.1** provides a summary of several socio-ecological studies classified by the methodological approach and the way in which they deal with the identified uncertainty.

In this chapter, an extensive sensitivity analysis applied in different stages of model development and application is presented. This is done with the sustainability dynamic model of Fuerteventura Biosphere Reserve (FSM), which was elaborated to contribute to a more balanced and multifunctional development of this socio-ecological system (Banos-González et al. 2013, 2015, Chapter 3). The SA has been applied to answer the following question:

i) Was the FSM built as parsimonious as possible? Would it be possible to reduce the number of parameters and achieve a more compact model without losing valuable information?

ii) How robust the conclusions derived from the model are? May they be taken into account in the decision-making process with sufficient level of confidence?

iii) Which parts of the system have the highest influence on sustainability outcomes?

iv) How does uncertainty affect the assessment of policies?

v) How does uncertainty affect the assessment of the vulnerability of the system to certain external changes?

In this chapter, a strategy based on sensitivity analysis has been developed to address the following objectives:

1. To improve model formulation.

2. To perform a detailed assessment of model robustness.

3. To identify system parameters which have the highest influence on sustainability as a basis to define efficient policies.

4. To explore how uncertainty affects the assessment of different policy options.

5. To analyse how uncertainty affects the assessment of the vulnerability of the socio-ecological system when certain external changes are considered.

Table 5.1. Selected socio-ecological studies which identify uncertainty. N/A: Not applied.

Reference	Study area	Management Problem	Methodological approach	Identified uncertainty	Treatments of uncertainty
Lacitiola et al. (2007)	Southern Italy	Tourism sustainability.	Model based on ecosystem quality.	Uncertainties generated by chaotic patterns.	N/A
Perch-Nielsen et al. (2010)	Switzerland	GHG intensity of the tourism sector	Bottom-up approach, focused on how to achieve consistent system boundaries.	Uncertainties from reported aviation emissions and from the overall effects of aviation on climate change.	The sensitivity of key indicators towards different assumptions in air transport's
Fiatova et al. (2011)	Not specified	Coastal zones	Agent-based modelling	Uncertainty associated to the effects of land taxes on the land use in a coastal zone.	N/A
Guan et al. (2011)	Chongqing (China)	Urban economy–resource–environment system	System dynamics	Differences in the developing tendencies of economic development, resource consumption, and environmental issues. As well as in the assessment of the most effective strategy to improve the integrated sustainability level.	Scenario simulation
Parrot et al. (2011)	St Lawrence River Estuary (Canada)	Marine wildlife protection	Agent-based decision support system	The nature of some whale responses to boats in the St. Lawrence region and worldwide the long-term consequences.	Validation against real scenarios
Xing and Dangerfield (2011)	Tourist island	Economic, environmental and social impacts of tourism development	System dynamics	Mentioned as part of the model testing process, and particularly in the forces behind tourism development.	N/A
Lauf et al. (2012)	Metropolitan region of Berlin (Germany)	Land use dynamics	Cellular automata model by integrating system dynamics.	Uncertainties related to residential choices.	N/A
Lesnoff et al. (2012)	Semi-arid rangeland (tropical Africa)	Cattle population dynamics	Leslie matrix model	Lack of reliable time series on herd sizes.	Sensitivity analysis
Carmona et al. (2013)	Guadiana Basin (Spain)	Water management and stakeholders participation	Participatory integrated modelling.	Farm decisions due to natural hazards and market fluctuations.	Bayesian Network and scenario analysis, assessesing uncertainties in water management
Ibáñez et al. (2013)	Dehesa rangelands (Spain)	Integrated assessments of land degradation.	System dynamics	The degree to which different factors would hasten degradation if they changed from their current typical values.	Plackette Burman sensitivity analisis
Vidal-Legaz et al. (2013)	Rural mountainous communities (Spain)	Land use changes	System dynamics	Trade-offs associated with land use changes.	Semi-gobal sensitivity analysis
Wei et al. (2013)	Tourist destination (Italy)	Interaction between tourism and environment	Mathematical viability theory	Uncertainty related with other tourist sites, in competition with the site under study.	N/A
Ropero et al. (2014)	River Adra, (Spain)	The catchment of the river Adra as a SES	Hybrid bayesian network	Cause–effect interactions between the components of the SES are subject to the uncertainty inherent in the system.	BNs manage uncertainty using probability theory
Xu et al. (2015)	Ha-Da-Qi industrial corridor (China)	Changes in landscape indices under four industrial development modes	System dynamics	Uncertainty of complex industry types, the products demand of small weighting factors and financial factors.	Scenario simulation

5.1.2. Parameters of the Fuerteventura Sustainability Dynamic Model

The Fuerteventura Biosphere Reserve sustainability dynamic model (FSM), as described in detail in Chapter 3, includes 520 variables, and 110 parameters. Parameter values (**Table 5.2**) were directly determined when data were available (e.g. statistics, local sources and scientific literature). When no reliable information was found, an automatic calibration process was carried out (Oliva 2003), using the optimization-calibration functionalities of Vensim DSS 5.8b, which allow to select the parameter values that maximize the simulation pay-off, using the Powell hill climbing algorithm (Vidal-Legaz et al. 2013). During this process, it was important that the parameter ranges were constrained to realistic levels for the target system, since it increases the power of the calibration without compromising the resulting model structure (Holmes and Johnstone 2010). All these parameters were subjected to a sensitivity analysis, as described in following sections.

Table 5.2. List of the parameters of the Fuerteventura sustainability dynamic model.

Parameter	Model value (Units)	Definition	Range of variation	References regarding range of variation
ABROAD	0.74 (Dmnl)	Proportion of tourists arrived from abroad	0.66 – 0.83	ISTAC (2015)
AIR	0.1899 (Dmnl)	Accommodation increase ratio (AC)	0.1424 – 0.2374	Standard range when no references (± 25%)
ARC	0.367 (Dmnl)	Adjustable runoff	0.2753 – 0.4588	Standard range when no references (± 25%)
AVERGOODS	1.2203e+009 (kg/year)	Average value of the Sea transportation of goods	0.763 e+009 – 1.698 e+009	ISTAC (2015)
AVERSTAY	9.06 (days)	Average length of the stay	7.53 – 11.11	ISTAC (2015)
B	33.2455 (Dmnl)	Intercept between births and GPDca	24.934 – 41.557	Standard range when no references (± 25%)
BIR BASE	-0.0188 (1/year)	Factor between births and GPDca	(-0.024) – (-0.014)	Standard range when no references (± 25%)
CFBUEU	3.37 (Dmnl)	Factor of urban built up which affects the houbara habitat	2.528 – 4.213	Standard range when no references (± 25%)
CO2FACTORgav	-300,000 (g CO_2/(year*ha))	CO_2 factor for gavias	(-300,000) – (-176,800)	Díaz et al. (2009); Padilla et al. (2010); Muñoz-Rojas et al. (2011)
CO2FACTORgc	-6.46e+006 (g CO_2/(year*ha))	CO_2 factor for golf courses	(-8.78e+006) – (-4.85e+006)	Standard range when no references (± 25%)
CO2FACTORirrig	-5e+006 (g CO_2/(year*ha))	CO_2 factor for irrigation area	(-6.25e+006) – (-3.75e+006)	Standard range when no references (± 25%)
CPRE	0.00082 (LU/(ha*mm))	Rainfall coefficient	0.00080 – 0.00084	Regression
desal CORRALEJO	1.46e+006 (m^3/Year)	Capacity of the desalination facilities in Corralejo	1.095 e+006 – 1.825e+006	Renforus (2014)
DIST1	316.14 (km/inhab)	Distance from Gran Canaria by passenger's flights (round trip)	237.105 – 395.175	Standard range when no references (± 25%)
DIST2	3,234.26 (km/inhab)	Distance from Madrid by passenger's flights (round trip)	2,425.695 – 4,042.825	Standard range when no references (± 25%)
DIST3G	6,973.66 (km/inhab)	Distance from Berlin by passenger's flights (round trip)	5,230.245 – 8,717.075	Standard range when no references (± 25%)
DIST3UK	5,604.92 (km/inhab)	Distance from London by passenger's flights (round trip)	2,101.845 – 3503.075	Standard range when no references (± 25%)

Parameter	Model value (Units)	Definition	Range of variation	References regarding range of variation
DIST4	2,291.12 km/journey	Distance from Puerto de Cádiz to Puerto del Rosario (round trip)	1,718.34 – 2,863.9	Standard range when no references (± 25%)
DVEF	189.6 (g CO_2/kwh)	Diesel vehicles CO_2 emission factor	142.2 - 237	Standard range when no references (± 25%)
ECO2E	360 (g CO_2/kwh)	Electricity CO_2 emision factor	351 – 410	Castellani and Sala (2013); Alacid et al. (2010); Trappey et al.(2012)
EECBR	829.495 (kwh/(inhab*year))	Population electric energy consumption base ratio, before considering the GPDca effect	622.1213 – 1,036.8688	Standard range when no references (± 25%)
EICF	2 (MJ/km)	Energy intensity conversion factor	1.75 – 2.75	Becken (2002) - Hunter and Shaw (2007)
eLGCC	0.0215 Ev/LU	Effect of the livestock over the carrying capacity of the Egyptian vulture (AC)	0.016 – 0.027	Standard range when no references (± 25%)
EVAPORATION	67,000 (m3/Year)	Annual evaporation rate from water reservoirs	30,150 – 67,000	HPF(1999)
EVTp	0.9 (Dmnl)	Evapotranspiration (after the improvement of model formulation by means of the SA, the model value is 0.315)	0.675 – 1.125	Standard range when no references (± 25%)
FCO2E	69 (g CO_2/MJ)	Flights CO_2 emissions	69 – 71.6	Becken (2002)
FLOWSEAR	8.692e-004 (1/year)	Volume flowing into sea ratio (HPF 1999)	6.519e-004 - 10.865e-004	Insensitive parameters. Removing from the model structure after OAT.
FLOWSPRINGR	4.8751e-006 (1/year)	Flow spring ratio (HPF 1999)	3.656 e-006 – 6.094 e-006	Insensitive parameters. Removing from the model structure after OAT.
FODDER YIELD	37705.5 (kg/(ha*Year))	Annual fodder yield	17,178.2 – 37,705.5	Palacios et al. (2008) and ISTAC (2014)
FUEL CONSs	804.812 (kg fuel/km)	Fuel consumption of ships by each kilometer	740.43 – 869.2	EnerTrans (2008)
GCR	0.0516 (1/year)	Gavias change ratio (AC)	0.0387 – 0.0644	Standard range when no references (± 25%)
GDPcaFACTOR	4,240 (ships)	Effect of the GDPca on sea transportation of goods	2,971 – 5,509	Regression
GOLFCONR	10,950 (m^3/(ha*Year))	Golf courses water consumption	10,950 – 11,000	Fuerteventura Cabildo (2013)
GOLFLOSR	0.2 (Dmnl)	Water loss in golf courses water supply	0.2 – 0.3	HPF (2013)
GVEF	95.312 (gCO_2/kwh)	Gasoline emission factor (vehicles)	71.48 – 119.14	Standard range when no references (± 25%)
HCRac	0.96 (Dmnl)	Houbara habitat change ratio due to active crops	0.73 – 1.21	Standard range when no references (± 25%)
HCRpermabandon	0.178 (Dmnl)	Houbara habitat change ratio due to permanent abandonment of gavias	0.134 – 0.223	Standard range when no references (± 25%)
HCRroads	15.509 (ha/km)	Houbara habitat change ratio due to roads	11.632 – 19.386	Standard range when no references (± 25%)
HCRtracks	8.42 (ha/km)	Houbara habitat change ratio due to tracks	6.315 – 10.525	Standard range when no references (± 25%)
HCRub	0.119 (Dmnl)	Houbara habitat change ratio per hectare of new urban built up	0.089 – 0.149	Standard range when no references (± 25%)
HOTEL ACCOMMODAT LAND DEM	0.0059 (ha/bed)	Demand of land by each nonhotel accommodation bed	0.0047 – 0.006	Government of Canary Island (2004).
ICR	0.001103 (1/year)	Irrigation change rate (AC)	0.00083 – 0.00138	Standard range when no references (± 25%)

Parameter	Model value (Units)	Definition	Range of variation	References regarding range of variation
IR	0.062 (Dmnl)	Infiltration ratio from rainfall	0.052 – 0.062	HPF (1999); Cabrera and Custodio (2012); HPF (2013)
IR gavias	0.2 (m/Year)	Infiltration ratio in gavias	0.2 – 0.4	HPF (1999); HPF (2013)
IRCONR	7,000 (m^3/(ha*Year))	Irrigation consumption ratio	4,631 – 7,000	HPF (1999); HPF (2013)
IRLOSR	0.43 (Dmnl)	Irrigation loss ratio	0.19 -0.43	HPF (2013)
ISLAND	0.18 (Dmnl)	Proportion of tourist arrived from other island of the Archipelago	0.13 – 0.223	ISTAC (2015)
Kc	0.35 (Dmnl)	Cereal coefficient	0.3 – 0.4	Insensitive parameters. Removing from the model structure after OAT
Kn	23.533 (Ev)	Egyptian vulture population carrying capacity natural, without considering the livestock effect	17.65 – 29.417	Standard range when no references (± 25%)
LOSS	0.31 (Dmnl)	Loss ratio for urban water supply	0.25 – 0.35	HPF (1999); HPF (2013)
MAX ACCOMMODATION	133,000 (beds)	Maximum number of beds	133,000 – 283,935	Gallardo and Cáceres (2010); Fuerteventura Cabildo (2013)
MF GDPca INMIG	1.24816 (Dmnl)	Effect of the GDPca on immigration (AC)	0.9361 – 1.5602	Standard range when no references (± 25%)
MFACTOR GDP	3.14604 (Dmnl)	Effect of the GDPreal on foreign tourists arrivals (AC)	2.3595 – 3.93255	Standard range when no references (± 25%)
MFACTOR IET	0.704086 (Dmnl)	Factor on the tourist choice index (AC)	0.5281 – 0.8801	Standard range when no references (± 25%)
MIR	0.6094 (1/year)	Maximum or intrinsic growth ratio for the Egyptian vulture (AC)	0.457 – 0.762	Standard range when no references (± 25%)
MOR	0.0036523 (1/year)	Mortality rate	0.0035 – 0.0037	ISTAC (2010)
NBEACH THRESHOLD	30 (m^2/inhab)	Normalized beach factor threshold	10 - 30	Government of Canary Islands (2008).
NEEfactor	1.13987e+007 (g CO_2/(year*ha))	Net ecosystem exchange factor	0.878 e+007 – 1.402 e+007	Regression
NGP	0.5 (Dmnl)	Net grazing proportion	0.29 - 0.5	Mata et al. (2000)
NONHOT ACCOM LAND DEM	0.0042 (ha/bed)	Demand of land by each nonhotel accommodation bed	0.0035 – 0.007	Government of Canary Island (2004).
NONHOT ACCOM RATIO	0.53 (1/Year)	Nonhotel accommodations ratio regarding the total tourist accommodation.	0.25 – 0.68	Government of Canary Island (2010).
NOTOURIST EMPLOY	0.249 (Dmnl)	Proportion of employment not linked to tourist	0.187 – 0.3111	Insensitive parameters. Removing from the model structure after OAT
PEGcpl	2.425e-005 (1/(km*year))	Probability of electrocution with corrective measures in power lines	1.819e-005 - 3.031 e-005	Standard range when no references (± 25%)
PEGspl	9.7e-005 (1/(km*year))	Probability of electrocution without corrective measures in power lines	7.275 e-005 – 12.125 e-005	Standard range when no references (± 25%)
PENINSULA	0.078 (Dmnl)	Proportion of tourist arrived from the Iberian Peninsula	0.021 – 0.136	ISTAC (2015)
PLRpc	0.00335 (km/inhab)	Power lines Ratio per capita	0.0024 – 0.0035	Aerial photointerpretation from GRAFCAM images.
preFACTOR	-2.25604e+006 ((g CO_2)/(year*ha*mm))	Rainfall factor on the NEE	-2.775 e+006 - (-1.737e+006)	Regression
ptotFACTOR	0.000326 (ships/inhab)	Effect of the total population on the sea transportation of goods factor	0.000245 – 0.000408	Standard range when no references (± 25%)

Parameter	Model value (Units)	Definition	Range of variation	References regarding range of variation
ratioG	0.61 (Dmnl)	Proportion of German tourists from the foreign total tourists	0.52 -0.63	ISTAC (2015)
ratioUK	0.38 (Dmnl)	Proportion of United Kingdom tourist from the total foreign tourists arrived to Fuerteventura	0.32 – 0.39	ISTAC (2015)
REUSR	0.35 (Dmnl)	Ratio of reusing urban reclaimed water	0 - 0.9	Stakeholders (pers. Com)
ROADSn	0.000358 (km/inhab/Year)	New roads demand ratio	0.00027 – 0.00045	Standard range when no references (± 25%)
RPOPAQUIFR	0.01 (Dmnl)	Population Water demand from aquifer ratio	0.01 - 0.12	HPF (1999); HPF (2013)
RPOPCONRbase	65.7 (m3/(Year*inhab)	Residential population consumption ratio	55.72 - 65.7	HPF (1999); HPF (2013)
RPSEWAGEPROP	0.6 (Dmnl)	Sewage proportion	0.45 – 0.75	Standard range when no references (± 25%)
RPTREATMENTP	0.91 (Dmnl)	Treatment water proportion from resident population.	0.73 - 0.9	HPF (2013); Fuerteventura Cabildo (2013)
RT	136.75 (years)	Average time of plant composition recovery (AC)	40 - 200	Otto et al (2006); Tzanopoulos et al. (2007)
RUNOFFcte	0.026 (Dmnl)	Runoff constant	0.025 - 0.026	ITGE (1990)
SCG	44 (ha/golf course)	Area occupied by golf course	40 - 45	Aerial photointerpretation from GRAFCAM images.
SCO2E	3,200 (g CO_2/kg fuel)	Ships CO_2 Emission factor	3,170-3,200	Deniz and Kilic (2010)
SEADES CONVR	0.45 (Dmnl)	Seawater desalination conversion ratio	0.45 – 0.55	Meerganz von Medeazza et al. (2007); Meneses et al. (2010); Pérez-González et al. (2012)
SEADESCAP	2.757e+007 (m^3/year)	Seawater desalination capacity	2.068e+007 – 3.446e+007	Insensitive parameters. Removing from the model structure after OAT
SEWAGE PROP TUR	0.57 (Dmnl)	Proportion of sewage water from tourist consumption	0.57 – 0.6	CIAGC (2011)
SFACTOR	691.1 (ships)	Ships factor. Intercept ships	476.9 – 905.3	Regression
shipCAPACITY	2.566e+009 (kg/ships)	Ship carrying capacity for goods	1.925 e+009 – 3.208 e+009	Standard range when no references (± 25%)
ST	79 (year)	Period of succession after the abandonment of agricultural areas	52 – 79	Abella (2010)
TCEO	0.254 (Dmnl)	Electric energy consumption ratio by other sectors	0.254 – 0.3	Government of Canary Island (2006)
TCEOne	0.27 (Dmnl)	Non electric energy consumption ratio by other sectors	0.2025 – 0.3375	Standard range when no references (± 25%)
TCNE	333.302 (kwh/(inhab*year))	Non electric energy consumption ratio by population	249.977 – 416.628	Standard range when no references (± 25%)
TCONBOV	17.3 (m^3/head of livestock)	Water consumption by each head of livestock (cows)	3.65 – 17.3	Insensitive parameters. Removing from the model structure after OAT.
TCONCAPROV	1.825 (m^3/head of livestock)	Water consumption by each head of livestock (goats and sheeps)	1.825 – 2	HPF (1999)
TCONPORC	2.87 (m^3/head of livestock)	Water consumption by each head of livestock (pigs)	2.87 – 3.65	HPF (1999)

Parameter	Model value (Units)	Definition	Range of variation	References regarding range of variation
TCV	13,816.1 ((kwh/(car*year))	Annual energy consumption ratio by each car	13,816.1 – 17,124.519	Martín-Cejas and Ramírez Sánchez (2010)
TEMIG BASE	0.084 (1/year)	Base emigration ratio	0.071 – 0.092	ISTAC (2010)
TES	6.405 (year)	Time to detect the overgrazing effects (AC)	4.804 – 8.006	Standard range when no references (± 25%)
TGEREURBpc	589.28 (kg/(inhab*year))	Urban waste generation per capita	569.4 - 589.28	Fuerteventura Cabildo (2013)
THRESHOLD OR	0.5305 (inhab/bed)	Profitability threshold for the occupancy rate.	0.5305 – 0.75	Government of Canary Islands (2008).
TINGBOV	16,607.5 (kg/(head*year))	Fodder consumption by each head of livestock (cows)	15,695 – 17,520	Insensitive parameters. Removing from the model structure after OAT.
TINGCAPROV	657 (kg/(head*year))	Fodder consumption by each head of livestock (goats and sheeps)	657 - 730	Monzón-Gil (2007)
TINGPORC	1,124.2 (kg/(head*year))	Fodder consumption by each head of livestock (pigs)	886.95 – 1,343.2	Insensitive parameters. Removing from the model structure after OAT.
TINMIGDPca	2 (year)	Time of the effect of the GDPca on the immigration (AC)	1.5 – 2.5	Standard range when no references (± 25%)
TKWM3	4.5 (kwh/m3)	Energy consumption for desalation	3.123 – 5.877	Einav et al (2003); Meerganz von Medeazza and Moreau (2007)
TMOTN	0.421658 (car/inhab)	Motorization index base (AC)	0.316 – 0.527	Standard range when no references (± 25%)
TPP	1 (Dmnl)	Non electric energy loss ratio (from primary energy to final energy)	0.75 – 1.25	Standard range when no references (± 25%)
TRACKSn	0.001719 (km/inhab/year)	New tracks demand ratio	0.0013 – 0.0022	Standard range when no references (± 25%)
TRECRES	0.07 (Dmnl)	Recycled waste ratio from the mixture of waste.	0.048 – 0.111	Fuerteventura Cabildo (2013)
TRECSELEC	49.57 (kg/(inhab* year))	Selective urban solid wastes collection ratio.	31.65 – 54.4	Fuerteventura Cabildo (2013)
TSUCVOpc	0.074 (ha/(inhab*year))	Built Urban and other uses per house ratio (AC)	0.064 – 0.074	Standard range when no references (± 25%)
TURCONR	126.02 (m3/(inhab*year))	Tourist water consumption ratio	101 – 126.02	HPF (2013)
WCO2E	2,200 (g CO_2/kg)	Waste CO_2 Emission factor	1,650 – 2,750	Standard range when no references (± 25%)

5.2. METHODOLOGY

5.2.1. Sensitivity analysis

Different sensitivity analysis (SA) techniques were applied, ranging from the simplest class of “One factor at a time” (OAT) screening techniques to general sensitivity techniques. Among them, in this work a local sensitivity analysis and a Monte Carlo simulation have been applied. The purpose is not to select one of the two methods but to benefit from their complementarities, regarding the objectives set out in section 5.1.1:

5.2.1.1. Objective 1: to improve model formulation, removing the less sensible parameters

One factor at a time (OAT) sensitivity analysis allows the identification of those parameters to which the model behaviour is not responsive. Then the model structure may be simplified, removing those parameters and achieving a more compact model without losing valuable information for the system (Holmes and Johnstone 2010).

Moreover, in a complex model as FSM, with more than 500 variables and parameters and high computational run times, the OAT was used as a previous step, "screening stage", for a general sensitivity analysis (Uusitalo et al. 2015). In spite of the shortcomings of the OAT method -since it does not take into account interactions resulting from the simultaneous variation of multiple parameters-, the method has its strengths in easy and rapid evaluation of effects of extreme parameter values and has been widely applied (Van Griensven et al. 2002; Sun et al. 2012; Moreau et al. 2013).

In this work, 18 target variables were selected by means of which the model behaviour was assessed (**Table 5.4**). Some of such variables are also sustainability indicators. The screening of the most and least sensitive parameters within the model was undertaken using the OAT sensitivity analysis function within Vensim and a sample size of 200 runs. The response to each one of the examined model parameters was tested using an arbitrarily selected range of ±25% variation around the default parameter value. Ford (1990) and Taylor et al. (2010) used ±20% and pointed out to other possibilities, as ±50%. Thus, the effect of each parameter on the model outputs may be compared based on a homogeneous range of variation. The sensitivity index ($S_{i,j}$, **Equation 5.1**, Jørgensen and Fath 2011) was calculated for years 2012 and 2025 as follows:

$$S_{i,j} = \left(\frac{OM_{i,t} - Om_{i,t}}{Ob_{i,t}} \right) \Big/ \left(\frac{PM_j - Pm_j}{Pb_j} \right) * 100 \qquad \textbf{(5.1)}$$

Where $S_{i,j}$ represents the sensitivity index of the target variable i to the parameter j; $OM_{i,t}$ and $Om_{i,t}$ are the maximum and minimum values of the ith target variable at time t; $Ob_{i,t}$ represents the base (default) model value of the ith target variable at time t; PM_j and Pm_j represent the maximum and minimum values of the jth parameter, respectively; and Pb_j is the base model value of the jth parameter.

Regarding this sensitivity index, the parameters will be classified into five categories: insensitive ($S_{i,j}$=0%), low sensitivity ($S_{i,j}$<10%), moderate sensitivity (10%≤$S_{i,j}$<50%), high sensitivity (50%≤$S_{i,j}$<100%) and very high sensitivity ($S_{i,j}$ ≥100%).

5.2.1.2. Objective 2: to assess the robustness of the model outputs

In order to achieve realistic SA results and avoid running the model under impossible conditions, which would distort the model behaviour and, therefore, the confidence on it would be lost, a screening phase was carried out using a new local SA. This time, each parameter was perturbed within an "acceptable" or reasonable range (Ford 1990; Arabi et al. 2007; Makler-Pick et al. 2011). This range may have a slightly different meaning: i) range in which it is expected to find the true value of the parameter; ii) range of real variability of the parameter in the system (observed or predicted variability); and iii) realistic values that a parameter might adopt for a certain management measure (degrees of freedom in a particular policy).

The local SA with acceptable ranges allowed to identify and select the most sensitive parameters ($S_{i,j}$>50%) for each of the 18 target model variables used to assess the model response. These acceptable ranges are important for the general sensitivity analysis, since they ensure that the parameters are constrained to realistic levels and will produce behaviour consistent with known facts (Graham et al. 2002).

Once the sensitive parameters for each target variable are identified, a Monte Carlo (MC) simulation was carried out, with a Latin Hypercube sampling (Hekimoğlu and Barlas 2010). This general sensitivity analysis was implemented to assess the effects of a simultaneous variation of all sensitive parameters for each variable. MC is well adapted when uncertainties affecting the factors are of different orders of magnitude, and when models may generate interactions between factors or have non-linear outputs (Lesnoff et al. 2012). A Latin Hypercube search (LH) has been applied as mechanism to ensure that the full reasonable range of each parameter is explored using a manageable number of runs (200 simulations). This is desirable for big models where each simulation takes a long time, as the FSM. LH is designed to reduce the required number of model runs needed to get sufficient information about the distribution in the outcome (Ford and Flynn 2005).

In order to obtain the confidence intervals of the model outputs to changes in the respective most responsive parameters, 18 Monte Carlo SA simulations were run (one per target variable). It has been used the Vensim tool for the MC simulation, which provides the 50%, 75%, 95% and 100% percentile bounds of the established (200 in our case) simulations run. According to Ford and Flynn (2005), such percentiles can approximately been interpreted as the corresponding confidence bounds.

The variation coefficient (VC_i, **Equation 5.2**) of the target model variables shown by the Monte Carlo simulation was calculated for years 2012 and 2025 as follows:

$$VC_{i,t} = \left(\frac{OM95_{i,t} - Om95_{i,t}}{\overline{O}_i} \right) * 100 \tag{5.2}$$

Where VC_i represents the relative variation of the target variable i respect to its mean value using 95% confidence bounds; $OM95_i$ and $Om95_i$ are the maximum and minimum values of the ith target variable at time t using 95% confidence bound, and $\overline{O}_i$ is the mean value of the target variable i.

Regarding this variation coefficient, the response of the target model to changes in the respective most responsive parameters will be classified into three categories: low response (VC_i<50%), moderate response (50%≤VC_i<100%) and high response (VC_i≥100%).

5.2.1.3. *Objective 3: to identify the places of the system which have the highest influence as a basis to define policies for improving sustainability*

The most responsive parameters from the OAT analysis may be useful in establishing future priorities, according to Grant and Swannack (2008). In complex socio-ecological system, it is often possible to find 'leverage points', that Meadows (1999) defined as places within a complex system where a small shift in one thing can produce big changes in everything.

In this work, the identification of leverage points is tried as basis to define potential policy options.

5.2.1.4. *Objective 4: to explore how uncertainty affects the assessment of different policy options*

It has been determined how a selection of seven indicators would react under different policy measures. These indicators, some of which were previously presented as target model variables, were selected on the basis of their direct relationship with the concerned policies. **Table 5.3** shows these seven indicators and their sustainability thresholds.

Table 5.3. Sustainability indicators included in the Fuerteventura sustainability model and thresholds.

Indicators	Units	Direction of change	Threshold	Meaning of the threshold	References of the thresholds
Ratio of tourists to residents (*tures*)	Dimensionless	Less is better	<0.3152	The ratio of tourist to local inhabitants should be lower than the threshold	Government of Canary Islands (2008).
Ratio between tourist accommodation and resident population (*ear*)	Dimensionless	Less is better	<97	Ratio of tourist accommodations, each 100 residents	Government of Canary Islands (2008).
Artificial land proportion (alp)	%	Less is better	<20%	Percentage of land modified (agriculture, urban, infrastructures)	Graymore et al. (2010)
High quality vegetation proportion (*hqp*)	Dimensionless	More is better	LCA>0.1394	0.139 represents the LAC (75%) from the value in 2009	Model value in 2009.
Overgrazing indicator (*oi*)	Dimensionless	Less is better	<1	Values above 1 mean overgrazing	Banos-González et al. (2015)
Houbara habitat proportion (*hhp*)	Dimensionless	More is better	LCA>0.75	0.75 is the Limit of Acceptable Change (75% of the 2009 value)	Model value in 2009.
Egyptian vulture population proportion (*Evp*)	Dimensionless	More is better	LCA>0.75	0.75 is the Limit of Acceptable Change (75% of the 2009 value)	Model value in 2009.

The establishment of thresholds for every indicator is a clear step forward in sustainability since they represent a reference for decisions and quantify what is acceptable regarding sustainability goals (Gallopin 1997; Moldan et al. 2012; Proelss and Houghton 2012). When there were no published thresholds for an indicator, a value based on a proportion of the value adopted for that indicator in 2009 was established, when Fuerteventura was declared a Biosphere Reserve (UNESCO 2009). In this work, 75% of the 2009 value was set. This is related to the concept of “Limit of Acceptable Change” (LAC, Stankey et al. 1985; Diedrich et al. 2011), since this proportion allows certain change due to socio-touristic development, but the threshold is still far from compromising the conservation goals.

Simulation results under Monte Carlo analysis for each indicator will determine whether the sustainability thresholds of the selected seven indicators might be exceeded under any of the analysed options when uncertainty is taken into account.

5.2.1.5. Objective 5: to analyse how uncertainty affects the assessment of the vulnerability of the system to certain external changes

A tool for adaptive governance and improving resources management should include the capacity to deal with uncertainty and changes, including external drivers. In order to incorporate a preliminary assessment of this capacity into our analysis of the FSM, two groups of scenarios were explored:

S.1) *Economic scenarios.* Two economic scenarios were considered:

> S.1.G) *Growth*. It is defined by the macroeconomic variables (GDPca, GDPout and TPI) showing an average behaviour similar to the 1996-2007 trend, since it represents a high growth period. It means around 2.65 times bigger than the average behaviour under BAU. Several authors (Alcamo et al. 2007; Qin et al. 2011; Schaldach et al. 2012; Matos et al. 2014) point to the importance of the socio-economic situation over the natural resources consumption, such as water and energy.
>
> S.1.R) *Recession*. The macroeconomic variables show an average behaviour similar to the 2008-2011, period of a deep economic recession.

S.2) *Climate change scenarios*. Model parameters were calculated on the basis of the CEDEX report (2011), for the A2 and B2 scenarios of the Special Report on Emission Scenarios (Nakicenovic and Swart 2000; Rodríguez Díaz et al. 2007). This represents a 10 and 14% of rainfall reduction and a 13 and 18% of increase in irrigation requirements in 2025 under A2 and B2 scenarios, respectively.

5.3. SENSITIVITY ANALYSIS RESULTS

5.3.1. Improvement of model formulation

Annex III records the sensitivity index of each target model variable to every parameter across the ±25% range. 54 out of 110 studied parameters have sensitivity below 10% for all target model variables, which may be considered as low sensitivity. 7 out of them were removed from the model structure, since they were no sensitive ($S_{i,j}$ =0% for all target variables): FLOWSEAR, FLOWSPRING, NOTOURIST EMPLOY, SEADESCAP, TCONBOV, TINGBOV and TINGPORC. In one case, the FODDER YIELD, has not been removed despite of being also insensitive for all target variables, due to its importance when policy options are implemented.

After removing these insensitive parameters, a new goodness of fit test for the 20 variables with available observed data series was carried out (see **Annex IV** for details), to confirm that the goodness of fit had not changed.

5.3.2. Detailed assessment of model robustness

After removing 7 parameters from the model structure, a new local SA was carried out, varying each parameter within its acceptable range (see **Annex III**). Under this more realistic range of variation, one parameter, Kc, became insensitive ($S_{i,j}$ =0% for all target variables) and was removed from the model structure; two parameters, GOLFLOSR and NBEACH THRESHOLD, reduced its sensitivity below 10%.

Another parameter, AVERSTAY, decreases its sensitivity below 50% for the variable per capita CO_2 emissions. The other parameters barely change their sensitivity.

Therefore, there are now 48 low-sensitivity parameters ($S_{i,j}$<10%), 28 moderate-sensitivity parameters (10%≤$S_{i,j}$<50%) and 26 high-sensitive parameters ($S_{i,j}$ ≥50%) (see **Annex III**). 18 out of these 26 parameters show high sensitivity for just one target variable and, therefore, their impact on the model response is very local. On the contrary, 5 of these high-sensitivity parameters are considered the most responsive (B, BIRBASE, MFACTOR IET, NGP and THRESHOLD OR), since each one of them is highly sensitive for five or more target variables, 3 of which (BIRBASE, MFACTOR IET, THRESHOLD OR) has $S_{i,j}$ ≥100% for five or more variables.

Results of the global sensitivity analysis (MC) are shown in **table 5.4**, which also presents the set of sensible parameters ($S_{i,j}$ ≥50%) for each target variable.

Results from the Monte Carlo SA show a moderate response of the model output to changes in parameter values. 9 out of the 18 analysed variables show a low response (variation coefficient below 50%); 7 target variables show a moderate response (variation coefficient between 50% and 100%); and 2 show a high response (variation above 100%): CO_2 pc and recycled waste.

Figure 5.1 shows the results of the Monte Carlo SA simulations. The dashed line indicates the *Base run* simulation. The red, green, blue and yellow areas account for the confidence bounds of 50%, 75%, 95% and 100% of the Monte Carlo simulations, respectively.

Table 5.4. Results of the MC sensitivity analysis. For each target variable, the most responsive parameters ($S_{i,j}$≥50% from Once at Time sensitivity analysis) were used. For details about parameters, see **Table 5.1.**

TARGET MODEL VARIABLE	**RESPONSIVE PARAMETERS**	**SENSITIVITY RESULTS ± 95% CONFIDENCE INTERVAL (in 2025)**
Built-up urban (*bu*)	AIR, B, BIR BASE, MF GDPca INMIG MFACTOR IET, THRESHOLD OR, TSUCVpc	10,335 ± 8,042 (Hectares)
High quality vegetation prop (*hqp*)	CPRE, BIR BASE, MFACTOR IET, NGP, RT	0.141 ± 0.12 (Dimensionless)
Gavias proportion (*gap*)	GCR, REUSR	0.058 ± 0.0015 (Dimensionless)
Overgrazing indicator (*oi*)	CPRE, NGP	0.518 ± 0.125 (Dimensionless)
Fodder importation needs (*fin*)	NGP, TINGCAPROV, THRESHOLD OR	0.575 ± 0.088 (Dimensionless)
Resident population (*respop*)	AIR, B, BIR BASE, MF GDPca INMIG MFACTOR IET, THRESHOLD OR	140,862 ± 118,391 (Inhabitants)
Equivalent tourist population (*etp*)	B, BIR BASE, MFACTOR IET, THRESHOLD OR	37,042 ± 17,705 (Inhabitants)
Houbara habitat proportion (*hhp*)	BIR BASE, MFACTOR IET, THRESHOLD RO	0.738 ± 0.213 (Dimensionless)
Egyptian vultures proportion (*Evp*)	NGP, eLGCC	1.113 ± 0.263 (Dimensionless)
Electric energy consumption (*enc*)	B, BIR BASE, MFACTOR IET THRESHOLD OR, EECBR, TCEO	1,030 ± 0.721 (Mwh/year)
Share of renewable energy (*SER*)	B, BIR BASE, MFACTOR IET, TCV, THRESHOLD OR,TMONT, TPP	0.011 ± 0.006 (%)
Per capita CO_2 emissions (CO_2 *pc*)	NEEfactor, preFACTOR, MFACTOR IET, THRESHOLD OR, AVERGOODS, FUEL CONSs	32.2 ± 37.3 ((Metric tonnes CO_2/(pc* year))
Groundwater recharge (*gwr*)	IR	17.26 ± 2.75 (Hm^3/year)
Groundwater pumping (*gwp*)	IRCONR, SCG, GOLFCONR	7.289 ± 0.31 (Hm^3/year)
Desalinated water (*desw*)	B, BIR BASE, MFACTOR IET, RPOPCONRbase, THRESHOLD OR	18.27 ± 12.25 (Hm^3/year)
Brine production (*brine*)	B, BIR BASE, MFACTOR IET, RPOPCONRbase, SEADES CONVR, THRESHOLD OR	20.26 ± 12.36 (Hm^3/year)
Treated sewage proportion (*sewage prop*)	RPTREATMENTP	0.845 ± 0.06 (Dimensionless)
Recycled waste (*recwas*)	B, BIR BASE, MFACTOR IET, TGEREURBpc, THRESHOLD OR, TRECRES	7,769 ± 7,951 (Tonnes/year)

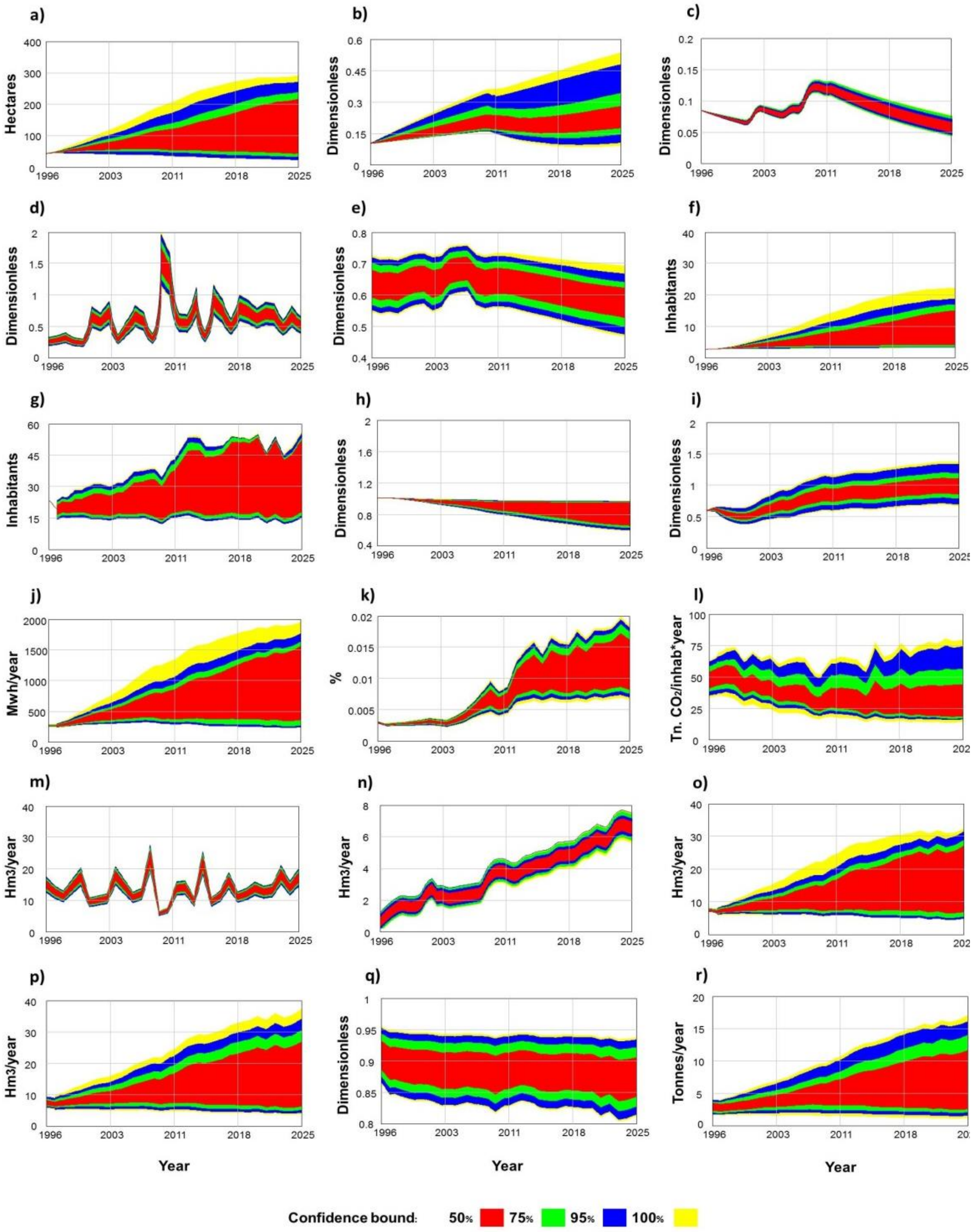

Figure 5.1. Monte Carlo SA to changes in sensitive parameter values (local sensitivity over 50%) for the target model variables: (a) Built-up urban, (b) High quality vegetation proportion, (c) Gavias proportion, (d) Overgrazing indicator, (e) Fodder importation needs, (f) Resident population, (g) Equivalent tourist population, (h) Houbara habitat proportion, (i) Egyptian vultures proportion, (j) Electric energy consumption, (k) Share of renewable energy, (l) Per capita CO_2 emissions, (m) Groundwater recharge, (n) Groundwater pumping, (o) Desalinated water, (p) Brine production, (q) Treated sewage proportion and (l) Recycled waste.

5.3.3. Which parts of the system have the highest influence on sustainability outcomes?

This section is based on the most responsive parameters from the local sensitivity analysis (**Annex III**). This analysis was used to identify the leverage points in the FSM, this is, where decisions can most effectively influence the performance of the system.

As mentioned in section 5.3.2, these most responsive parameters are: B, BIRBASE, MFACTOR IET, THRESHOLD OR and NGP. Since the first three parameters (B, BIRBASE and MFACTOR IET) come from automatic calibration, the potential of using the two later parameters to develop management measures is analysed.

Regarding the socio-tourist dynamics, it is intended to assess a policy aimed at controlling the effect of the tourism over some key variables: resident population, equivalent tourist population and accommodation places. Two measures are assessed, one based on policies proposed so far, and another one based on the model leverage points.

Measure 1. *The limitation of new tourist accommodations based on a maximum number of tourist beds*. The maximum tourist accommodation capacity, determined by MAXACCOMMODATION parameter, would be reduced by 10%, in line with the proposal of the General Regulation Directives and the Canary Islands Tourism Regulation Directives -TRD, henceforth- (Government of the Canary Islands 2003).

Measure 2. *The limitation of new tourist accommodations, based on an occupancy rate threshold*. The development of new tourist accommodation beds, is partially determined by the occupancy rate. The SA identified the parameter THRESHOLD OR as a leverage point. In this measure, this parameter is increased by 10%, meaning that the accommodation facilities should mantain a higher occupancy rate before new infrastructure is built-up.

Simulation results (**Fig. 5.2**) show that a 10% change in MAXACCOMODATION, would mean 4.8%, 1.4% and 4.4% change in resident population, equivalent tourist population and touristic accommodation, respectively in 2025; whereas a 10% change in THRESHOLD OR would mean 24.5%, 22.4% and 29.4% change, respectively.

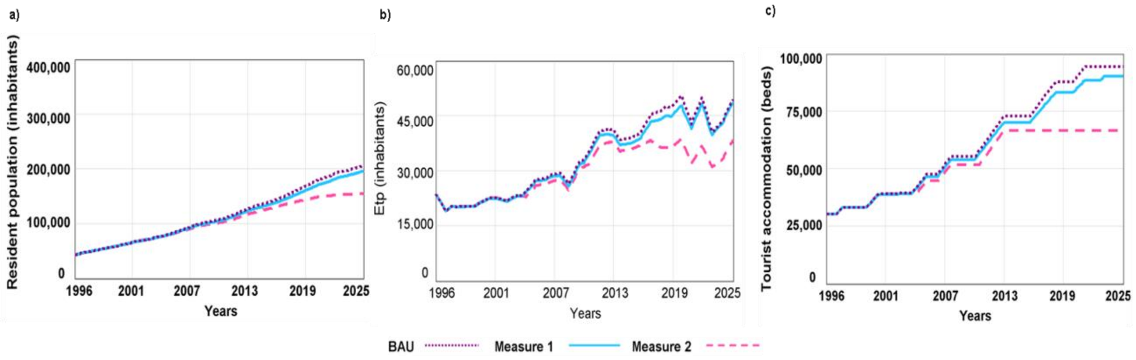

Figure 5.2. Simulation results under different measures for indicators: a) resident population; b) equivalent tourist population (*etp*) and c) tourist accommodation.

Regarding the land use dynamics, it is intended to assess a policy aimed at improving some indicators as high quality vegetation (*hqp*), the overgrazing indicator (*oi*) and the landscape (*li*) indicator. Two measures are assessed:

Measure 3. *The reduction of grazing pressure on high-quality natural vegetation by restoring gavias*. This measure, supported by the Abandoned Gavias Restoration Plan (Fuerteventura Cabildo 2009), is tested by increasing 10% the reuse of urban reclaimed water (REUSR) to restore abandoned fields (gavias) and to cultivate fodder for cattle feeding in order to reduce the needs of grazing.

Measure 4. *Direct reduction of grazing pressure*. This measure considers a 10% reduction of the proportion of grazing on the island (NGP). The parameter NGP was identified as a leverage point.

In this case, simulation results (**Fig. 5.3**) show that a 10% change in REUSR, would mean around 3.8%, 3.7% and 6.3% change in *hqp*, *li* and *oi*, respectively in 2025; whereas the 10% change in NGP would mean 6%, 5.5% and 10% change in those indicators, respectively.

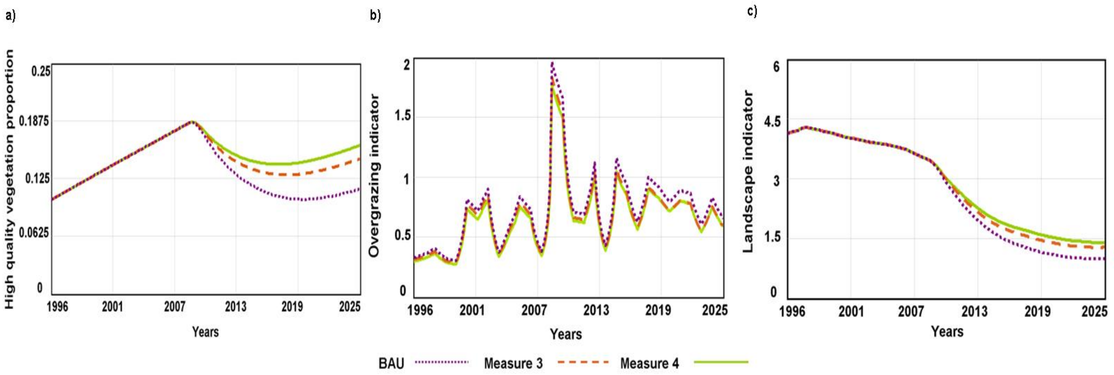

Figure 5.3. Simulation results under different measures for indicators: a) high quality vegetation proportion; b) overgrazing indicator and c) landscape indicator.

5.3.4. How does uncertainty affect the assessment of policies?

Base on the aforementioned leverage parameters, two policy measures were defined aiming at different goals:

Policy I. Limitation of the new tourist accommodations. Increase in THRESHOLD OR to 75%, proposed by Government of Canary Islands (2008). This policy might be implemented by different measures, such as a tax to the accommodation capacity.

Policy II. Reduction of grazing to protect the soil and the high-quality natural vegetation. This measure considers that the NGP is reduced from 50% under BAU to 29%, as in the case of the neighbour Tenerife Island (Mata et al. 2000).

To explore how uncertainty affects the assessment of such policies, a set of indicators and their thresholds were used (**Table 5.3**). **Table 5.5** shows the mean value of the Monte Carlo simulation for each indicator and the 95% confidence bounds for BAU and for the two policy measures.

The ratio of tourists to locals (*tures*) would exceed its sustainability threshold under BAU in 2025, both the mean value and when its associated uncertainty with 95% confidence bound is considered. Under Policy I, the equivalent tourist population and the resident population, numerator and denominator of the *tures*, would reduce almost 13% and 66% compared to BAU, respectively. This bigger decrease in the residents would lead to the worsening of around 29% of this indicator under Policy I (**Table 5.5**).

Table 5.5. Monte Carlo simulations results for the sustainability indicators under BAU, Policy I and Policy II.

INDICATORS	THRESHOLDS	MC SIMULATION RESULTS in 2025		
		BAU	POLICY I	POLICY II
Ratio of tourists to residents (*tures*)	<0.3152	0.329 ± 0.277 (0.053-0.606)	0.426 ± 0.189 (0.236-0.616)	0.329 ± 0.277 (0.053-0.606)
Ratio between tourist accommodation and resident population (*ear*)	<97	61.77 ± 64.27 (0 – 126.04)	74.14 ± 53.2 (20.84-127.24)	61.77 ± 64.27 (0 – 126.04)
Artificial land proportion (alp)	<20%	6.83 ± 4.74 (2.09-11.57)	3.658 ± 1.845 (1.813-5.503)	6.83 ± 4.74 (2.09-11.57)
High quality vegetation proportion (*hqp*)	LCA>0.1394	0.141 ± 0.119 (0.021-0.261)	0.146+-0.109 (0.038 – 0.255)	0.287 ± 0.1306 (0.144 – 0.405)
Overgrazing indicator (*oi*)	<1	0.518 ± 0.125 (0.399 – 0.644)	0.518 ± 0.125 (0.399 – 0.644)	0.380 ± 0.009 (0.371 – 0.389)
Houbara habitat proportion (*hhp*)	LCA>0.75	0.738 ± 0.213 (0.525 – 0.952)	0.9349 ± 0.034 (0.901 – 0.959)	0.7384 ± 0.213 (0.525 – 0.952)
Egyptian vulture population proportion (*Evp*)	LCA>0.75	1.113 ± 0.263 (0.85 – 1.376)	1.138 ± 0.267 (0.871 – 1.405)	0.745 ± 0.1001 (0.645 – 0.845)

The same pattern shows the *ear* indicator, with a worsening around 20% under Policy I. The mean values of the simulation results of *ear* would be far from the threshold under both simulations (BAU and Policy I). Nevertheless, when uncertainty is taken into account, this sustainability threshold might be exceeded.

The proportion of artificial land (*alp*) would be reduced by almost half under Policy I regarding BAU, since the reduction of the tourist and resident population would slow down the land uptake processes. Simulation results show that Fuerteventura is still far from the sustainability threshold for this indicator, even considering the uncertainty.

The reduction of the land uptake expected under Policy I would lead to an improvement of the houbara habitat proportion (*hhp*). The threshold for this indicator would be exceeded under BAU, but the indicator would be kept far from such threshold under Policy I, even taking its uncertainty into account.

The proportion of Egyptian vultures (*Evp*) would not exceed its threshold under BAU nor Policy I, even considering its uncertainty. However, this indicator would slightly improve (around 2%) under Policy I.

Regarding Policy II, the high quality vegetation proportion (*hqp*) would double as compared to BAU. According to mean values, this indicator would be far from its threshold, under both BAU and Policy II. However, when uncertainty is taken into account this threshold might be exceeded under BAU, but not under Policy II.

The overgrazing indicator (*oi*) also would show an improvement around 27% under Policy II. In any case, both under BAU and Policy II, the threshold would not be exceeded, even taking uncertainty into account.

On the contrary, the reduction in the grazing proportion considered under Policy II would lead to a decrease in 33% in *Evp*, exceeding its threshold, since the grazing cattle constitutes the basis of their diet, whereas this indicator would show an increasing trend between 2012 and 2025 under BAU.

Summarizing, under BAU the mean values of 2 out of 7 indicators (*tures* and *hhp*) would exceed its threshold; but when uncertainty is taken into account, 4 out of 7 might exceed them. Regarding Policy I, the mean values of 1 out of 7 indicators (*tures*) would exceed its threshold; but when uncertainty is considered, 3 out of 7 might exceed them. Under Policy II, the mean values of 3 out of 7 indicators (*tures, hhp* and *Evp*) would exceed its threshold; but when uncertainty is taken into account, 4 out of 7 might exceed them.

5.3.5. How does uncertainty affect the assessment of the vulnerability of the system to certain external drivers?

Table 5.6 presents the simulation results concerning BAU, two economic scenarios (growth and recession) and two climate change scenarios (A2 and B2).

5.3.5.1. Economic scenarios

The increase in tourist and resident population and, thus, the demand of new infrastructures expected under the economic growth scenario, would give raise to an improvement of the *tures* and *ear* around 5.4% and 7.8% respectively, compared to BAU. On contrast, *alp* and *hhp* would worsen around 7.5% and 4.1% under this scenario, respectively (**Table 5.6**). Not noticeable changes are expected for the remaining indicators.

Under an economic recession scenario, the *tures* and *ear* would worsen around 3% and 5% comparing to BAU, since the resident population would decrease. On the contrary, the *alp* and *hhp* would improve around 4% and 3%, respectively, thanks to the restraint in the new infrastructures demand. No changes are expected for the remaining indicators.

According to the mean values of the simulations results under economic scenarios, the number of indicators which would overcome their thresholds would be reduced from two to one, as compared to BAU (*hhp* under growth and *tures* under recession). Nevertheless, when uncertainty is taken into account, four indicators would exceed their thresholds (*tures, ear, hqp* and *hhp*), in BAU as much as in both economic scenarios.

5.3.5.2. *Climate change scenarios*

Under scenarios A2 and B2, indicators *hqp* and *oi* would worsen. For the *hqp*, the reduction would be around 12.7% and 21.5% regarding BAU, under A2 and B2 respectively. For the *oi*, this worsening would be around 26.7% and 32.6% for A2 and B2 compared to BAU. No changes are expected for the remaining indicators.

According to the mean values, the climate change scenarios would increase the number of indicators exceeding their thresholds from two to three, as compared to BAU (since the threshold of *hqp* would also be exceeded under both climate scenarios). When uncertainty is taken into account, the indicators exceeding their thresholds increase to 4, as under BAU.

Table 5.6. Monte Carlo simulations results for the sustainability indicators under exterbak drivers

INDICATOR	THRESHOLDS	BAU	ECONOMIC	SCENARIOS	CLIMATE CHANGE	SCENARIOS
			GROWHT	RECESSION	A2	B2
tures	<0.3152	0.329 ± 0.277 (0.05-0.61)	0.312 ± 0.244 (0.07 – 0.56)	0.339 ± 0.289 (0.05 – 0.63)	0.329 ± 0.277 (0.05-0.61)	0.329 ± 0.277 (0.05-0.61)
ear	<97	61.77 ± 64.27 (0 – 126.04)	56.96 ± 53.12 (0.84 – 113.1)	64.69 ± 69.26 (0 – 133.95)	61.77 ± 64.27 (0 – 126.04)	61.77 ± 64.27 (0 – 126.04)
alp	<20%	6.83 ± 4.74 (2.09-11.57)	7.34 ± 4.91 (2.43 – 12.25)	6.55 ± 4.72 (1.83 – 11.27)	6.83 ± 4.74 (2.09-11.57)	6.83 ± 4.74 (2.09-11.57)
hqp	LCA> 0.1394	0.141 ± 0.119 (0.02-0.26)	0.142 ± 0.12 (0.02-0.26)	0.141 ± 0.119 (0.02-0.26)	0.123 ± 0.127 (0 – 0.25)	0.111 ± 0.138 (0 – 0.25)
oi	<1	0.518 ± 0.125 (0.4 – 0.64)	0.522 ± 0.127 (0.39 – 0.65)	0.514 ± 0.125 (0.39 – 0.64)	0.656 ± 0.088 (0.57 – 0.75)	0.687 ± 0.092 (0.59 – 0.78)
hhp	LCA>0.75	0.738 ± 0.213 (0.53 – 0.95)	0.708 ± 0.230 (0.48 – 0.94)	0.759 ± 0.1957 (0.56 – 0.96)	0.738 ± 0.213 (0.53 – 0.95)	0.738 ± 0.213 (0.53 – 0.95)
Evp	LCA>0.75	1.113 ± 0.263 (0.85 – 1.38)	1.112 ± 0.281 (0.83 – 1.39)	1.113 ± 0.263 (0.85 – 1.38)	1.113 ± 0.263 (0.85 – 1.38)	1.113 ± 0.263 (0.85 – 1.38)

5.4. DISCUSSION

The discussion will address the questions outlined in the Introduction.

5.4.1. Was the FSM built as parsimonious as possible? Would it be possible to reduce the number of parameters and achieve a more compact model without losing valuable information for the system?

An important aim of the parameter sensitivity analysis is to allow the possible reduction in the number of parameters that must be estimated, thereby reducing the computational time required for model calibration (Bastidas et al. 1999; Muleta and Nicklow 2005).

8 out of the 110 studied parameters, were removed from the model structure, since they were no sensible ($S_{i,j}$ =0% for all target variables): FLOWSEAR, FLOWSPRING, SEADESCAP, Kc, TCONBOV, TINGPORC and NOTOURIST EMPLOY. This has resulted in a more compact and parsimonious model

Results on **Annex IV** demonstrate that without these insensitive parameters, there is no degradation in the quality of the calibrated model performance (Bastidas et al. 1999).

5.4.2. How robust the conclusions derived from the FSM are? May they be taken into account in the decision-making process with sufficient level of confidence?

Decision-makers are increasingly interested to understand the uncertainties of the models. Uusitalo et al. (2015) underlined that only evaluating the nature and extent of the uncertainties in the system, the model can provide decision-makers with a realistic picture of the possible outcomes, since is impossible to predict with certainty the result of each management decision.

Sensitivity analysis is a critical tool for evaluating the reliability of model outputs (Hekimoğlu and Barlas 2010). The results of the detailed assessment of robustness (Section 5.3.2) showed that there is enough confidence on model outcomes. 76% of parameters show low to moderate sensitivity according to the local SA, whereas 16 out of 18 model target variables show low to moderate variation according to the MC analysis.

Particularly, the results of the local SA show that the model displays generally low to moderate sensitivity to changes in parameters values. Model displays high sensitivity ($S_{i,j}$>50%) for 26 parameters (24% of total). 10 out of them display sensitivity above 100%, meaning that the model interactions might exacerbate the input variation in such parameters (Perz et al. 2013). However, for the majority of them, only one target variable showed high sensitivity. Only 5 parameters (B, BIRBASE, MFACTOR IET, THRESHOLD OR, NGP) exhibited high sensitivity for more than 5 target variables. 4 out of them belong to the socio-tourist sector. This is consistent with the finding of many authors (Gössling and Hall 2006; Xing and Dangerfield 2011; von Bergner and Lohmann 2013) who state that tourism is highly influenced by external drivers, which include economic, environmental, political, social, technological and even attitudinal dimensions, which provide a high degree of uncertainty.

At high levels of model complexity, individual sources of uncertainty are more likely to exhibit interactions that can greatly increase overall model uncertainty. Therefore, in models with many interactions among sources of uncertainty, overall uncertainty may be amplified (Perz et al. 2013). In the FSM, the Monte Carlo simulation results show that 2 out of 18 target variables would change markedly (variation bigger than 100% respect to the mean value with 95% confidence bound) using their respective combination of most responsive parameters (**Table 5.4**). These MC results mean that decision-makers should take with caution the policy options and measures involving variables with a high uncertainty. In Fuerteventura, this is particularly the case for the per capita CO_2 emissions and the waste generation.

According to Uusitalo et al. (2015), as the decisions should be made based on prevailing knowledge but also acknowledging the gaps in it, transparent representation of uncertainty is recommendable on each level of modelling and stage of decision-taking. Moreover, uncertainty should be considered a normal component of decisions and, instead of inaction, it should appeal to the prudence of policy makers (Schouten et al. 2014; Song et al. 2015). The precautionary principle should be applied concerning the uncertainty analysis: the higher the uncertainty, the less risky the policy should be.

5.4.3. Which parts of the system have the highest influence on sustainability outcomes?

The identification of the leverage points in the FSM, this is the most responsive parameters from the OAT analysis, may be useful in establishing future priorities, where decisions can most effectively influence the performance of the system (Güneralp and Barlas 2003; Buchholz et al. 2007; Sterk et al. 2009; Baroni and Tarantola 2014). Hjorth and Bagheri (2006) pointed that people often manage to find them by intuition, but generally can drive to wrong decisions.

In this work the potential of using leverage points to develop more effective measures is shown. Leverage points-based measures with other measures with a similar aim proposed by different agents have been compared, by means of two simple cases. Simulation results (**Fig. 5.2**) showed that bigger changes in key socio-ecological variables were achieved under Measure 1 (10% change in the occupancy rate threshold, a leverage point), than under Measure 2 (10% change in the maximum number of beds, based on the TRD –the Canary Islands Tourism Regulation Directives- of the Government of the Canary Islands, 2003). These results are consistent with other authors (Oreja-Rodríguez et al. 2008; Martín-Cejas and Ramírez 2010; Santana Jimenez and Hernández 2011) who suggested that the moratorium set out by the TRD has been shown insufficient to stop the increasing number of beds and the impacts it involves.

Regarding policies aimed at improving some indicators related to the land use sector, simulation results (**Fig. 5.3**) also showed bigger changes in those indicators under Measure 4 (10% of reduction on the net grazing proportion, a leverage point), than under

Measure 3 (10% of change in the water reuse ratio, based on the Abandoned Gavias Restoration Plan of the Fuerteventura Cabildo, 2009).

These results show that measures based on the identified leverage points have a higher impact than others, as many of those proposed by different agents. This analysis may help decision-makers to reconsider misconceived plans and policies, in order to direct the politic and economic efforts to more effective measures.

5.4.4. How does uncertainty in model outcomes affect the assessment of policies?

It is widely acknowledged that uncertainty needs to be accounted in impact studies for decision support. Scenario and policy analysis represents a tool to deal explicitly with different assumptions about the future, which is inherently uncertain (Refsgaard et al. 2007; Liu et al. 2008). However, the existing models are often deterministic, without any indication of the amount of uncertainty or expected variation around this value (Holzkämper et al. 2015). Uusitalo et al. (2015) highlighted that models which include the uncertainties related to the management options may be of considerable added value for the decision makers.

In this work it has been assessed how a set of indicators included in the model would react under two policy measures based on the identified leverage points. The focus is not only the mean values of these indicators, but also their associated uncertainty.

Regarding Policy I, the limitation of the new tourist accommodations would lead to the improvement of two key sustainability indicators as compared to BAU: the artificial land proportion (*alp*) and the houbara habitat proportion (*hhp*). Even when uncertainty is considered, the sustainability thresholds for *alp* and *hhp* would not be exceeded under Policy I. On the contrary, the ratio of tourists to residents (*tures*) and the ratio between tourist accommodation and residents (*ear*) would increase regarding BAU (see **Table 5.5**), exceeding their thresholds in all the analysed simulations. This can be explained by the increase in the resident population, the denominator in both indicators, which would be bigger under BAU than under Policy I. This illustrates how possible misunderstandings may appear when relative sustainability indicators are considered alone. Relative indicators should be taken with caution to avoid errors in the diagnosis about sustainability (Figge and Hahn 2004; Mori and Christodoulou 2012).

Regarding Policy II, the high quality vegetation proportion (*hqp*) and the overgrazing indicator (*oi*) would improve. In case of *hqp*, this improvement would distance the indicator from its threshold, even considering its uncertainty. On contrast, the Egyptian vulture population proportion (*Evp*) would decrease under Policy II, exceeding its threshold.

Uusitalo et al. (2015) underlined the crucial importance of coming up with an uncertainty estimate to go along with each of the model outcomes, since it has a large impact on how the decision support model will behave and, therefore, has potential for changing the management recommendations that are drawn from the model. In this sense, it might be wondered if the overcome of some sustainability thresholds would have gone unnoticed when only the mean values of the simulations were considered. As aforementioned, the number of indicators which might exceed their threshold when uncertainty is taken into account would increase from 2 to 4 under BAU, from 1 to 3 under Policy I and from 3 to 4 under Policy II. These policies coul be a priori considered as environmentally sound and, in effect, Policy I reduces the number of indicators exceeding their thresholds when considering mean values. However, when uncertainty is taken into account, an important finding arises: not only BAU, but also both policy options are riskier than expected, since they show higher number of indicators exceeding their thresholds.

5.4.5. How does uncertainty affect the assessment of the vulnerability of the system to certain external drivers?

A real tool for sustainable management and decision-making in socio-ecological systems should include the capacity to deal with uncertainty and changes in external drivers (Folke et al. 2005). With the aim of governing and managing a transition toward more sustainable development paths, numerous authors underlined the resilience perspective (Lambin 2003; Folke 2006). The resilience in socio-ecological systems could be interpreted as the capacity of the system for learning and adaptation, in addition to the ability to persist disturbances (Carpenter et al. 2001; Daw et al. 2009). The FSM has incorporated a preliminary assessment of the vulnerability of this SES and its capacity to adapt and persist external disturbances. In this work, two groups of scenarios have been analysed: economic scenarios (growth and recession) and climate change (A2 and B2) scenarios.

Simulation results under economic scenarios show that the number of indicators exceeding their sustainability thresholds when considering mean values does not increase respect to BAU. However, under both climate change scenarios, the number of exceeding thresholds would increase from two to three (the ratio of tourists to residents, the high quality vegetation proportion and the houbara habitat proportion). These analyses, although preliminary, point to the vulnerability of this hyperarid insular socio-ecological system to the climate change, as suggested by Caujape-Castells et al. (2010), Lloret and González-Mancebo (2011) or Fernandes et al. (2015).

Furthermore, that vulnerability to external drivers might be higher than perceived when only mean values are considered, since the number of indicators exceeding their thresholds is always higher when uncertainty is taken into account

These preliminary results also suggest that the Fuerteventura socio-ecological system might be more reactive to policy intervention (as Policy I) than to external economic drivers, both economic growth (S.1.G) and recession scenarios (S.1.R). For instance, while under S.1.R, indicators such as *alp* and *hhp* would improve around 4% and 3%, respectively, under Policy I, this improvement would reach almost 50% and 27%, respectively. This highlights the impact of policy actions (and inactions) in the management of this SES and underlines the responsibility of decision-makers to address measures to contribute to a more balanced and sustainable development for the Fuerteventura socio-ecological system.

The work presented here reveals some shortcomings. On one side, three out of the five parameters which present high sensitivity were determined by an automatic calibration process, since no other information was available. There is also a lack of knowledge about the acceptable range of change in several parameters. Such knowledge would allow to gain higher certainty in model outputs. Finally, the scenario assessment presented here has only a preliminary character. Results showed by climatic change scenarios point to the need of performing a more extensive and detailed analysis of the vulnerability of the Fuerteventura socio-ecological system to the ongoing climatic change. These shortcomings will be addressed in subsequent work. However, this work shows the usefulness of an extensive sensitivity analysis applied to different stages of model development. It has also been revealed advantageous so as to improve model applications for sustainable management and decision-making.

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CHAPTER 6

Dynamic modelling of the potential habitat loss of endangered species: the case of the Canarian houbara bustard

6. DYNAMIC MODELLING OF THE POTENTIAL HABITAT LOSS OF ENDANGERED SPECIES: THE CASE OF THE CANARIAN HOUBARA BUSTARD (*CHLAMYDOTIS UNDULATA FUERTEVENTURAE*)*

Abstract

A dynamic modelling approach has been applied to analyse the habitat loss of the Canarian Houbara Bustard (*Chlamydotis undulata fuerteventurae*). This tool allows to assess the effects of the socio-economic and environmental interactions on the threatening factors for the habitat and to carry out prospective analysis. Results showed a potential habitat loss around 13% along the period 1996-2011, being the land uptake and the increase in new roads and tracks the most contributing factors. After model testing, a set of scenarios was explored. Under the Business As Usual scenario (BAU), around 20% of the habitat would be lost at the end of the period (2012-2025). The impact of the economic growth scenario on the habitat would mean around 13% of additional loss respect to BAU, whereas under the recession scenario the loss might be around 12% lower than BAU. The policy of gavias restoration -traditional farming systems- would mean almost 6% of additional loss, respect to BAU. These results suggest the existence of a potential trade-off among the ecosystem services offered by restored gavias and the conservation of the houbara habitat. This trade-off, which should be addressed within the management processes, points to the need for compensatory measures to guarantee the conservation goals.

Keywords: *Chlamydotis undulata fuerteventurae*; habitat loss; threatening factors; dynamic model; arid island; scenarios.

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6.1. INTRODUCTION

Conservation of endangered species in populated or managed areas requires interdisciplinary approaches, which facilitate an integral knowledge on habitat use and population size, as well as the dynamic of their threatening factors. System dynamic models (SDMs) allow to integrate the socio-economic and environmental aspects and to take into account their interactions along time (Jørgensen and Bendoricchio 2001; Martínez-Fernández et al. 2013). This dynamic approach has proven very useful to assess the effects of these interactions on biodiversity and to carry out prospective analysis, including the case of keystone species in arid environments (Silva et al. 2010; Pérez et al. 2012).

This chapter is focused on the dynamics of the arid island of Fuerteventura (The Canary Islands, Spain) and one of its keystone species: the Canarian Houbara Bustard (*Chlamydotis undulata fuerteventurae*), to show how SDMs could represent a helpful tool for the management of populated areas and the conservation of their threatened species.

The Houbara Bustard is a medium-sized bird inhabiting arid plains and stony hills with low slope, coastal plains and consolidated sandy areas. Classified as “vulnerable” (IUCN 2009), it is divided into *C*. *u*. *undulata* and *C*. *u*. *fuerteventurae.* Whereas the former is distributed from northern Mauritania to Egypt (Bourass and Hingrat 2015), the later is a Canarian endemic subspecies designated as “in danger” on the Spanish Red List (Lorenzo 2004). It is one of the Canarian terrestrial birds with smaller distribution area, with almost all population living exclusively in Lanzarote and Fuerteventura (Martín and Fernández-Palacios 2001; Carrascal et al. 2008, Schuster et al. 2012).

The available censuses reviewed herein for 1994 (Martín et al. 1997), 2004/2006 (Carrascal et al. 2006; Lorenzo 2005; Lorenzo et al. 2007; Carrascal et al. 2008), and 2011 (Schuster et al. 2012) show a 29% decrease along the period 2004/2006-2011 (Schuster et al. 2012). The loss of habitat seems to be the main threatening factor for the houbara population (Lorenzo 2004; Carrascal et al. 2008). The houbara habitat in Fuerteventura has suffered a series of negative effects along the last decades as a consequence of the tourist and housing activities which have expanded within the houbara habitat (Martín and Fernández-Palacios 2001; Palacios and Tella 2003). In addition, new roads and unpaved tracks have spread all over the island, fragmenting the houbara habitat and causing disturbances to the populations of houbara (Palacios and Tella 2003; Carrascal et al. 2008). These factors have been previously found as negative in Fuerteventura as in other places sheltering populations of other houbara sub-species, like in North Africa (Hingrat et al. 2007).

Despite of the big tourist and housing expansion underwent in Fuerteventura along the last decades, the changes in the habitat used by the houbara have not been deeply studied. A better understanding of the recent dynamics of the factors threatening the potential habitat of houbara is essential to advance specific protection mechanisms (Lorenzo 2004) and to implement comprehensive policies regarding sustainable development and conservation of the biodiversity (Otto et al. 2007).

Moreover, prospective analyses are also necessary to explore the potential risks in the medium and long term. To this aim, in this work the following objectives are addressed:

1. To apply the FSM to better understand the main threatening factors for the habitat, and how they are linked to the general dynamics of the Fuerteventura.
2. To determine which of the identified threatening factors have contributed most to the total loss of potential habitat in the recent period (1996-2011).
3. To use the model to assess the expected effects of different future scenarios and policy options on the houbara potential habitat.

6.2. METHODOLOGY

6.2.1. Contribution ratio of factors determining the houbara potential habitat

In order to generate the houbara potential habitat map, both quantitative and qualitative habitat preferences were applied. The quantitative habitat preference factors established by Carrascal et al. (2008) were first applied. These factors are: 1) slope, 2) unpaved tracks density and 3) paved roads density (**Table 6.1**). For each of these factors, a quantitative range was established, where the houbara was found during the censuses, constraining the potential habitat that may shelter the species within the island. For each factor and its range, the potentially available area for the houbara in Fuerteventura was identified by means of a GIS, using data and maps from the Canarian cartographic server (GRAFCAN).

Table 6.1. Factors and ranges falling within the houbara preferences.

Factor	Ranges or categories falling within the Houbara preferences	Data source
Slope	Up to 8.4 % (Carrascal et al. 2008)	Slopes map (GRAFCAN)
Soil grain size	Sandy soils or small rocks, never over the bedrock. Qualitative. (Lorenzo et al. 2007).	Lithology map (GRAFCAN)
Vegetation	All but tall vegetation plus bare ground. Qualitative. (Carrascal et al. 2008)	Vegetation map 2002 (GRAFCAN)
Land use	Abandoned gavias. Qualitative. (Carrascal et al. 2008)	Based on land use map 2002 (GRAFCAN)
Urban settlements	Up to 103.5 m street density/20 ha (Carrascal et al. 2008)	Generated in this work based on the 2002 street maps (GRAFCAN)
Density of tracks	Up to 421.5 m/20 ha (Carrascal et al. 2008)	Generated in this work (digitizing) from ortophoto 2002
Density of paved roads	Up to 103.5 m/20 ha (Carrascal et al. 2008)	Generated in this work (digitizing) from ortophoto 2002

In addition to the above quantitative preference ranges, the houbara preferably selects its habitat based on the following qualitative characteristics (Carrascal et al. 2006; Palomino et al. 2008a; Schuster et al. 2012): i) open and flat areas; ii) sandy soils or small rocks, never over the bedrock; iii) short to moderately tall vegetation, but never tall vegetation or trees; iv) areas of low human disturbance (natural land covers and abandoned gavias). Hence the potential habitat of houbara based on these qualitative factors was also constrained (**Table 6.1**). Those areas where either its lithology or vegetation clearly limit the presence of the houbara were excluded (**Table 6.1**). Regarding agricultural uses, abandoned gavias may shelter low densities of houbaras, also referred as secondary habitat (Collins 1984, Martín et al. 1996; Seddon and van Heezik 1996). Therefore, abandoned gavias were not excluded from the potential habitat of the houbara. While a sporadic source for food resources, active gavias are also a source of human interference (Lavee 1985; Hingrat et al. 2007), and do not constitute potential habitat of houbara, as well as more intensive agriculture uses.

By GIS procedures, the potential houbara habitat in 2002 was estimated, when all required information was available, and then each factor-specific contribution ratio to the habitat loss was obtained (**Fig. 6.1**). These ratios were later used to parameterise the houbara sector in the general dynamic model of the sustainability of the Fuerteventura Biosphere Reserve (FSM).

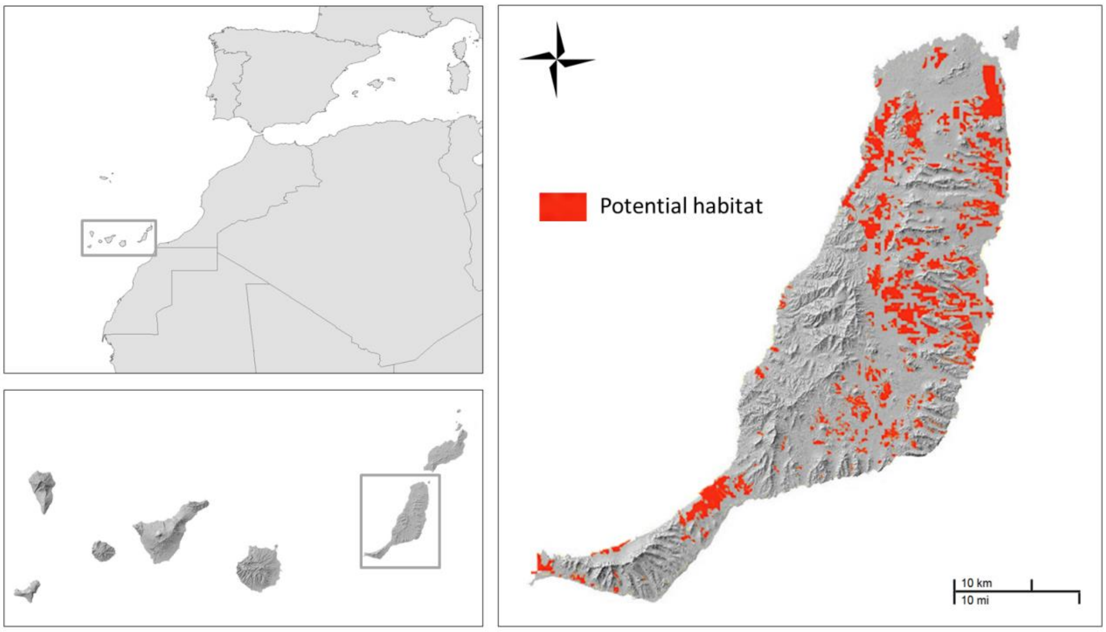

Figure 6.1. Location of the potential habitat of houbara in Fuerteventura (The Canary Islands).

6.2.2. Dynamic modelling of houbara potential habitat

The houbara potential habitat (**Fig. 6.2**) is included as a sector in a more general dynamic system model (Jørgensen and Bendoricchio 2001) of the sustainability of the Fuerteventura Biosphere Reserve (FSM, see Banos-González et al. 2013, 2015 and Chapter 3 for details), developed as a tool to improve the understanding of the key processes of this socio-ecological system.

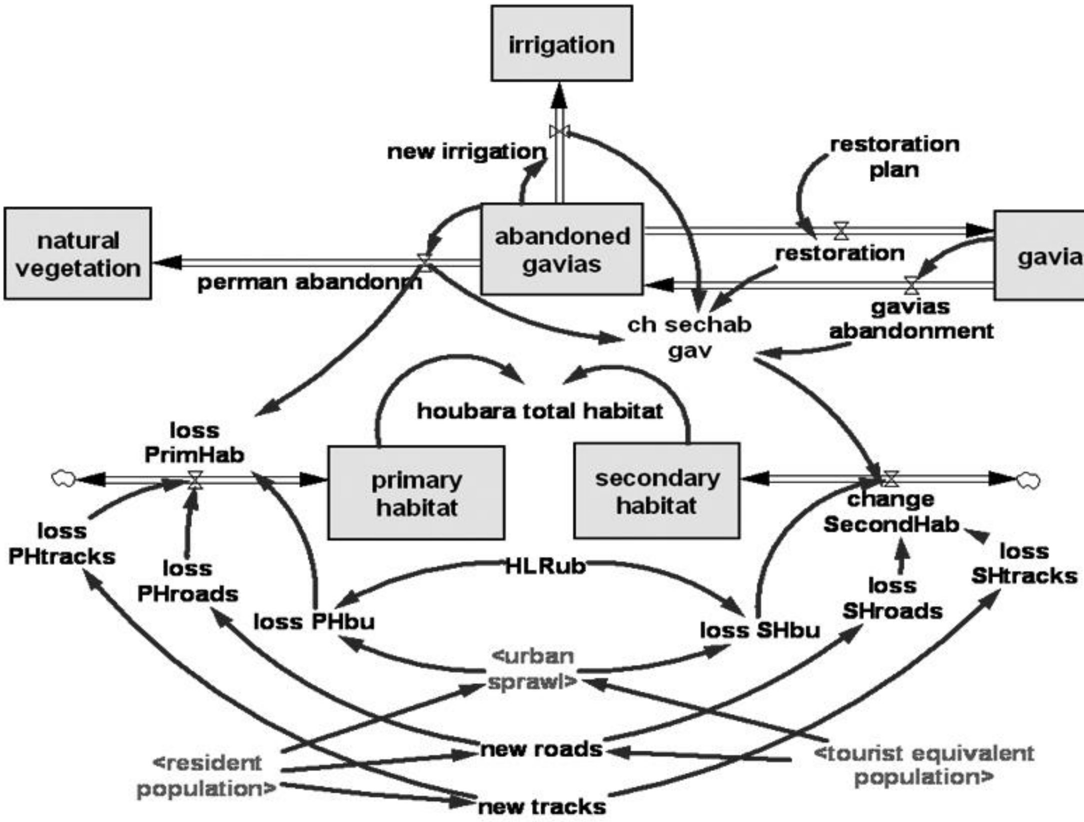

Figure 6.2. Model sector of the houbara potential habitat.

It has been considered two state variables for the houbara potential habitat, the primary and secondary habitat, differing in houbaras density (Lorenzo et al. 2007; Martín et al. 1997). The houbara sector takes into account the effects of other model variables representing the main factors governing the habitat loss, basically land use changes. The primary and secondary potential habitat are affected by the increase in urban areas (residential and tourist facilities) and infrastructures (road and tracks), which remove both types of habitat and by the increase in active crops (gavias and irrigated crops), which reduce the area of abandoned gavias, part of the secondary habitat (**Eq. 6.1** and **Eq. 6.2**). The urban sprawl is promoted by the tourist and resident population demands. The demand for new roads depends on total population (both resident and tourist population) whereas the demand for new tracks is based on the resident population, since tracks are mainly used by the rural communities. Finally the area of active crops changes according to irrigation increase and to gavias restoration measures. The main parameters of the houbara model sector correspond to the previously established contribution ratio of each threatening factor (urban areas, roads, tracks and active crops) to the habitat loss.

$$ch_{PH} = (par * PHP_{pa}) - (bu * PHP_{bu}) - (nr * PHP_{nr}) - (nt * PHP_{nt}) \qquad \textbf{(6.1)}$$

where ch_{PH} means the annual change rate in the primary potential habitat; *par* is the abandoned gavias to natural vegetation succession rate; PHP_{pa} is the proportion of natural vegetation which is part of the primary habitat; *bu* is referred to the annual change of urban areas; PHP_{bu} means the proportion of these urban areas which negatively affect the primary habitat; *nr* and *nt* denote the new paved roads and unpaved tracks which annually appear on the island, respectively; PHP_{nr} and PHP_{nt} are the proportion of the new roads and tracks which negatively affect the primary habitat, respectively.

$$ch_{SH} = (ch_{ag} * SHP_{ag}) - (par * (1 - SHP_{pa})) - (bu * SHP_{bu}) - (nr * SHP_{nr}) - (nt * SHP_{nt}) \quad \textbf{(6.2)}$$

where ch_{SH} means the annual change rate in the secondary potential habitat; ch_{ag} is referred to the annual changes in abandoned gavias area (from and to active gavias); SHP_{ag} is the proportion of abandoned gavias which is part of the secondary habitat; par is the abandoned gavias to natural vegetation succession rate; SHP_{pa} is the proportion of natural vegetation which is part of the secondary habitat; bu is referred to the annual change of urban areas; SHP_{bu} means the proportion of these urban areas which negatively affect the secondary habitat; nr and nt denote the new paved roads and unpaved tracks which annually appear on the island, respectively; SHP_{nr} and SHP_{nt} are the proportion of the new roads and tracks which negatively affect the secondary habitat, respectively.

6.2.3. Scenario Analysis

The FSM has been applied to assess the impact of several scenarios and management measures to the houbara potential habitat in the long term (2012-2025). They are relatively probable scenarios, based on observed behaviours along the calibration period (1996-2011). In this chapter, the following scenarios and measures were assessed:

i) Business as usual scenario (BAU). Observed trends are maintained - no change in model parameters-. The macroeconomic variables (the Canarian GDP, the GDP of the most important markets for outbound tourism, and the tourist prices index) were calculated on the basis of the 2006-2011 average behaviour.

ii) Scenario of economic growth. It is defined by the macroeconomic variables showing an average behaviour similar to the 1996-2007 trend, which means around 2.65 times bigger than BAU mean values.

iii) Scenario of economic recession. It is defined by the macroeconomic variables with an average behaviour similar to the 2008-2011 period, when they showed negative values.

iv) Gavias restoration. Under this management option, the abandoned gavias are restored using the recycled wastewater originated on the island. The aim of this measure is to contribute to increase the crop production and to decrease the grazing pressure on high quality natural vegetation, among other reasons.

6.3. RESULTS

6.3.1. Contribution ratios to habitat loss

For year 2002 a total of 29,633 hectares of potential habitat (17.86% of the island) were estimated, including 1,920 ha of abandoned gavias, as part of the secondary habitat. **Table 6.2** presents the factor-specific contribution ratios to the habitat loss.

Table 6.2. Factor-specific contribution ratios to the habitat loss.

Factor	Contribution ratio to habitat loss	Units
Paved roads	15.509	ha /km
Unpaved roads	8.42	ha /km
Urban areas	0.119	dimensionless
Active crops	0.117	dimensionless

6.3.2. 1996-2011 simulation period

Within the simulation period there are only estimations of potential habitat for years 1996, 2002 and 2011. Model results for such years are consistent with such estimations (**Fig. 6.3a**), although the scarce number of observed data do not allow a quantitative assessment of goodness of fit.

The combined effect of the factors threatening the houbara habitat has led to the decrease from around 30,000 hectares in 1996 to around 26,000 in 2011 (**Fig. 6.3a**). Primary habitat decreases by around 11% respect to the around 11,000 hectares in 1996, whereas the secondary habitat decreases near 15% respect to around 19,000 hectares in 1996 (**Fig. 6.3b**). The 13.3% loss in total potential habitat is mainly explained by the increase in urban areas (**6.4a**), roads (**6.4b**) and tracks (**6.4c**). Land uptake is caused by the raise in the socio-tourist activity and in total population, which also leads to new roads. The increase in tracks is explained by the growth of resident population. Roads have a higher unitary impact over the houbara habitat than tracks, although, given the high tracks density, the aggregated effect of the latter is bigger. The raise in active crops due to irrigation and particularly due to a local policy of gavias restoration (**6.4d**), reduces the area of abandoned gavias and therefore negatively affects the houbara secondary habitat, which decreases at a slightly higher rate than the primary habitat (**Fig. 6.3b**).

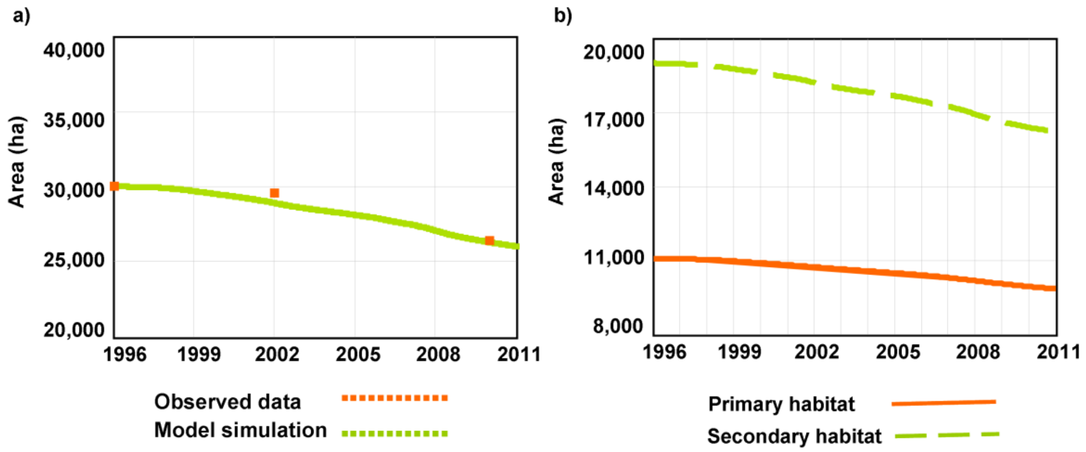

Figure 6.3. a) Model results (1996-2011) and observed data (1996, 2002, 2011) for the total houbara potential habitat in Fuerteventura; b) Model results for the primary and secondary houbara habitat.

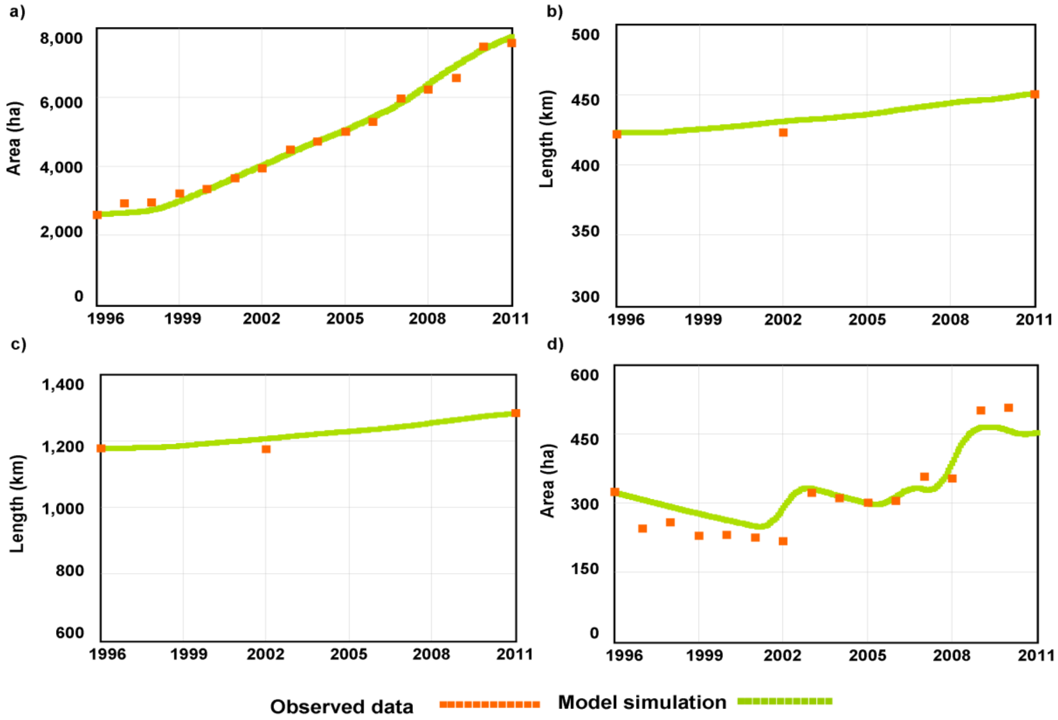

Figure 6.4. Observed data and simulation results in the period 1996-2011 for the factors affecting the houbara potential habitat. a) Urban area; b) Length of roads; c) Length of tracks; d) Area of active gavias.

Between 1996 and 2011 there is in average an annual habitat loss of 268 hectares, a 0.89% annual loss ratio of total habitat. Along this period, the loss ratio shows a clear increasing trend, despite a high interannual variability. The factor which contributes most to such loss is land uptake (137 hectares per year in average), although the impact of disturbances caused by roads and tracks (86 hectares per year in average) are not far from the loss caused by direct habitat transformation (**Fig. 6.5**).

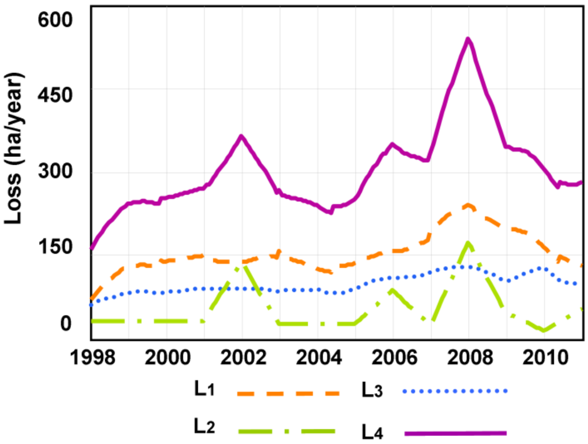

Figure 6.5. Contribution of each factor to the loss of houbara potential habitat, where L_1: loss due to built-up urban; L_2: loss due to new crops; L_3: loss due to roads and tracks; L_4: total habitat loss.

6.3.3. Scenario analysis (2012-2025) results

Under the BAU scenario, the houbara potential habitat would decrease to around 20,700 ha (**Fig. 6.6a**) at an average loss ratio almost 388 ha/year. It means that the total habitat would be 19.6% less in 2025, due to the urban sprawling and the increasing demand of paved roads and tracks (**Fig. 6.6b**).

Under an economic growth scenario around 5,700 ha of potential habitat would be lost, which would suppose almost a 22.2% loss along the 2012-2025 period. It means an additional loss around 13% under this scenario regarding the BAU scenario at the end of this period.

The habitat loss under an economic recession scenario would be around 17.3% along the 2012-2025 period (**Fig. 6.6a**), at an average loss ratio around 345 ha/year (**Fig. 6.6b**). It would mean a potential houbara habitat loss around 11.5% lower than BAU scenario.

The management option of a more extensive gavias restoration would give rise to a reduction of the potential habitat to around 20,400 ha in 2025, which means 5.7% of additional loss, regarding the BAU scenario.

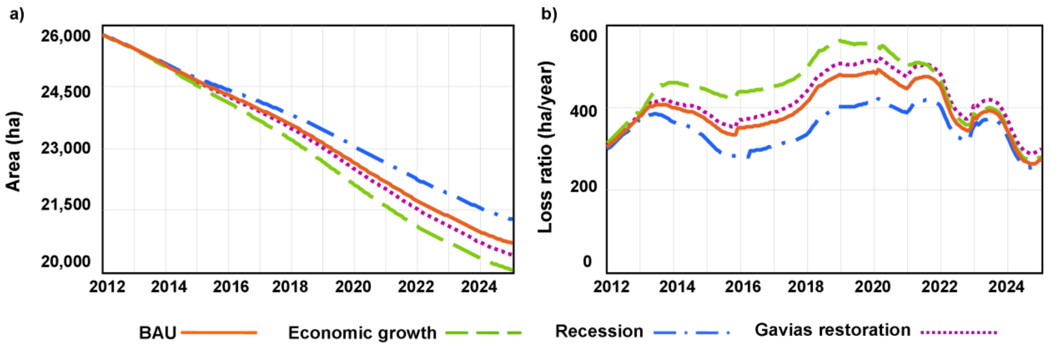

Figure 6.6. a) Houbara potential habitat under the BAU, economic growth, recession and gavias restoration scenarios; b) Loss ratio of houbara habitat under such scenarios.

6.4. DISCUSSION

Results from the dynamic model show a habitat loss around 13.3% along the period 1996-2011, which is consistent with the reported decreasing trend in the Fuerteventura houbara population for such period (Martín et al. 1997; Carrascal et al. 2006; Lorenzo 2005; Lorenzo et al. 2007; Carrascal et al. 2008; Schuster et al. 2012). The loss of primary habitat is of particular concern, since it is the habitat with the highest densities of houbaras and is also scarcer than the secondary habitat. Despite the loss in total potential habitat can be considered as relatively low, this might have a higher impact on the houbara population, which between the 2004/2006 to 2012 censuses showed an overall decrease around 29% (Schuster et al. 2012).

Modelling results also show that land uptake is the factor contributing most to the habitat loss (187 hectares per year in average in the period 1996-2011). However, indirect effects as disturbances caused by roads and tracks have jointly led a noticeable habitat loss of 86 hectares per year in average. The importance of these factors has also been suggested by previous authors (Lorenzo 2004; Carrascal et al. 2008), although such effects had not been previously quantified. These factors should be taken into account, since indirect effects could be perceived as less important or even go unnoticed in land planning and conservation processes. The effect of the new agricultural areas is lower than the other factors during the calibration period.

The changes in the potential habitat do not fully explain the changes in the Fuerteventura houbara population. This may be explained considering additional processes not addressed in this work, particularly habitat fragmentation, which has a major impact on the demographic dynamics due to the decrease in average patch size, higher perimeter/area ratio and longer distance between patches (Saunders et al. 1991; Andrén 1994; Fahrig 2003). Furthermore, there are some evidences about the existence of additional threatening factors for the houbara populations not accounted for in this work, such as houbaras electrocution on power lines (Lorenzo 2004; Lorenzo and Genové 2007; Schuster et al. 2012). Besides, Le Cuziat et al. (2005) noticed that the houbara clearly avoids the areas with a high stock of goats and sheeps. It has been pointed out that a high livestock density has a negative effect on the houbara due to disturbances and the reduction in breeding success (Lavee 1985; Schuster et al. 2012) and a potential mortality of chicks caused by trampling. Although Koshkin et al. (2014) found that the effects of livestock on houbara habitat structure were subtle in the Bukhara study area (Uzbekistan), overgrazing is recognized as a conservation problem for a variety of birds (Pavel 2004; Palomino et al. 2008b).

The scenario analysis for the 2012-2025 period has shown that the habitat loss trend would go on in the future under a “Business as usual” scenario and might increase under an economic growth scenario, in which new tourist and residential infrastructures are demanded. The model results show a moderate influence of the studied economic scenarios on the potential habitat trends, in line with the well known effect of tourism and urban development on the avifauna (Palomino and Carrascal 2007; Zuberogoitia et al. 2014).

The reduction in abandoned gavias under a gavias restoration policy has shown a slight negative effect on the secondary habitat of houbara. Despite of the limited effect of this policy on the habitat loss, it is important to identify this trade-off in case of more extensive restoration measures, since this would have a higher effect on the houbara habitat. Trade-offs between the economic and ecological dimensions are well known (Young et al. 2005; McShane et al. 2011; Thompson et al. 2014). Nevertheless, it is also important to identify less obvious trade-offs within environmental objectives and policies, such as those involving the gavias restoration. Between the positive effects of gavias restoration it has pointed out those related with the aquifer recharge and the landscape quality, since this traditional capturing runoff system is perceived as high quality agro-natural landscape (Díaz et al. 2011). However, this environmental measure would reduce the secondary habitat of the endangered houbara. Therefore, compensatory measures should be implemented to guaranty this species conservation, such as more effective measures to prevent the loss in the primary habitat of the species, by searching for alternative planning options (Young et al. 2005; Gangoso et al. 2006; Illera et al. 2010; Pérez-García et al. 2014) or applying stronger controls on the expansion of existing or new urban developments as well as new roads and tracks.

Furthermore, although this species is not considered a good surrogate for more general biodiversity aspects as species richness (Carrascal et al. 2012), it is a keystone specie attracting attention, raising awareness on more general conservation needs and may also encapsulate the needs of other species on steppe areas and arid environments (Le Cuziat et al. 2005; Carrascal et al. 2008; Palomino et al. 2008a).

Future works, focused on a houbara population model, will take into account other factors driving the houbara demographic dynamics, including habitat fragmentation, power lines and the effect of additional disturbance factors such as livestock.

Our approach could be applied to other arid systems, once adapted to their specific conditions and target species, in which the indirect effects arising from different trends or management options could threaten the conservation goals.

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CONCLUSIONS

CONCLUSIONS

1. As contribution to the sustainability assessment of insular socio-ecological systems (SES), a dynamic model of the sustainability of Fuerteventura Biosphere Reserve (FSM) has been developed and calibrated for the 1996-2011 period. The FSM has 520 variables, 22 out of which are state variables and 13 are forcing inputs. There are five sectors: socio-tourist, land uses, flagship species, environmental quality and water resources. The FSM has been satisfactorily tested regarding goodness of fit with excellent (MAPE and NRMS lower than 10%) or good degree of fit (MAPE and NRMS between 10 and 20%) for most of the 20 variables with available observed data series. This and other testing procedures, as the successful 25 extreme condition test, support the usefulness of the model as a tool to understand this SES and analyse its sustainability.

2. The model has enabled the integration of 37 sustainability indicators, which facilitates an integral and dynamic assessment of the system and the analysis of the interaction between key variables and indicators. The results highlight the effectiveness of using dynamic tools as FSM to identify and quantify potential trade-offs, not only between socioeconomic development and environmental goals, but also between different sustainability indicators under the same environmental policy measure, as shown by the conservation of high quality vegetation and the conservation of a endangered scavenger species, or between the desalinated water demand and the per capita energy use. These trade-offs may often go unnoticed when only a set of static indicators is used.

3. The FSM has been applied to assess the Fuerteventura Biosphere Reserve Action Plan (AP), regarding its environmental sustainability goals (to maintain the landscape and the high-quality natural vegetation; to restore abandoned traditional agricultural areas; to minimise the dependence on fodder importation; to reduce the dependence on external, non-renewable energy resources and to conserve key species), sustainability indicators and proposed policy measures, as well as the internal coherence among all these features. These measures mainly deal with the production of renewable water, the limitation of grazing pressure, the restoration of gavias and the reduction of the fodder importation needs on the island. For this purpose, the behaviour of ten indicators, integrated in the FSM and whose sustainability thresholds were set out, were analysed under these policy measures for the 2012-2025 period. The results showed that none of these policy measures would meet the sustainability thresholds of four indicators (the landscape indicator, the proportion of renewable energy, the per capita primary energy use and the carbon dioxide emissions). Hence, it may be concluded that the policy measures derived from the Action Plan are insufficient to address some of its key environmental goals, particularly those related to the landscape and energy issues. Therefore, more ambitious actions should be adopted to meet such goals, such as those in line with the EU agenda for renewable energy.

4. Simulation results allowed to prioritise among the analysed policy measures derived from the AP using the remaining six indicators (the high quality vegetation proportion,

the overgrazing indicator, the active gavias proportion, the fodder importation needs proportion, the houbara habitat proportion and the Egyptian vulture population proportion) and their sustainability thresholds. Seven out of the eight policy measures would result in some of the sustainability thresholds being exceeded. Following the rule "Threshold out, measure out", only one measure, aimed at cropping fodder on restored gavias (traditional land farming system) to feed cattle, would not see any of these thresholds exceeded. Thus, it might be assigned the highest priority among the analysed measures. Nevertheless, this option would present certain trade-offs involving other indicators. For example, this measure would affect the Egyptian vulture population, since the grazing cattle form the basis of their diet. Hence, some compensation measures should be incorporated.

5. Sensitivity analysis has been revealed as a powerful tool in all stages of model development and application of SES models, being able to provide important insights to policy makers and end users. Regarding model building, the SA has allowed the improvement of the model formulation with the "One factor at a time" (OAT) screening technique. Eight no sensitive parameters were removed, making the model more compact and parsimonious. The SA has also allowed a detailed assessment of robustness. The Monte Carlo simulations showed a low (variation lower than 50% respect to the mean value) to moderate response (variation between 50% and 100%) for 16 out of the 18 target model variables to changes in parameters values, which support enough confidence on model outcomes.

6. Regarding model application and, more specifically, the definition of policy measures, the SA has also allowed the identification of the leverage points of the model, this is, the parameters to whose changes the model is more responsive. Results points to the potential of using these leverage points to develop more effective measures, as compared with other measures with the same objective proposed by different agents. The higher effectiveness of leverage-based measures has been shown regarding the objective of reducing grazing in the high quality natural vegetation and regarding the objective of controlling the tourist accommodations growth.

7. The SA has also allowed to explicitly consider and incorporate the uncertainty in the assessment of policies and scenarios. Conclusions regarding whether some objectives are achieved or whether certain sustainability thresholds might be exceeded may change when uncertainty is taken into account. Monte Carlo simulations applied to the leverage-based policy measures showed that for several indicators their sustainability thresholds would not be exceeded when mean values are considered, but such thresholds might be overcome when the uncertainty range with 95% confidence bound is taken into account. Under the BAU (Business as Usual) scenario, the number of analysed indicators which would exceed their thresholds would increase from 2 to 4 out of 7. Under Policy I (Limitation of the new tourist accommodations), the number of indicators exceeding thresholds would shift from 1 to 3 out of 7, whereas under Policy II (Reduction of grazing to protect the soil and the high-quality natural vegetation), such increase would be from 3 to 4 out of 7. Therefore, the potential risks related to the overcome of sustainability thresholds may go unnoticed without considering the uncertainty. Similar conclusions were found regarding the preliminary assessment of the vulnerability of this SES to some external drivers, as the considered socio-economic and climate change scenarios.

8. Under both considered climatie change scenarios (A2 and B2), the number of indicators whose mean value exceeding their thresholds would increase from 2 to 3 out of 7 considered indicators. Although preliminary, these results point to the vulnerability of this hyperarid insular socio-ecological system to the ongoing climate change.

9. Results regarding policy measures and scenarios suggest that the Fuerteventura socio-ecological system might be more reactive to policy intervention than to economic external drivers. This has been shown by indicators as the artificial land proportion, which changes around 4%-7% as compared to the BAU value under the economic scenarios, but it would be 46% lower than the BAU value under a measure to control the occupancy rate in tourist accommodations. This underlines the responsibility of decision-makers to address measures to contribute to a more balanced and sustainable development for the Fuerteventura socio-ecological system.

10. Regarding the dynamics of the houbara potential habitat, the simulation results are consistent with the available estimations for years 1996, 2002 and 2011, showing a loss around 13% along the 1996-2011 period. The BAU scenario would give rise to almost 20% of habitat loss between 2012-2025, whereas the loss would be around 13% higher and 12% lower than BAU for the economic growth and recession scenarios, respectively. Moreover, the use of the model has allowed to identify trade-offs between the conservation of the houbara habitat and other environmental policies, such as the restoration of abandoned gavias, since they constitute part of the houbara secondary habitat.

ANNEX I

Mathematical formulation of the model

(*In alphabetical order*)

abandoned gavias=INTEG (abandonment-permanent abandonment-newirrig-gavias restoration,GAV ABAND INIC)

Area covered by abandoned gavias. Units: ha

abandonment=active gavias*GCR

Ratio of gavias abanonment. Units: ha/Year

ABROAD=0.74

Proportion of tourists arrived from abroad (Source: ISTAC). Units: Dmnl

accomodation ch=IF THEN ELSE(ch or>0:AND:or-1>THRESHOLD OR, tourist accommodation capacity *AIR*rem new accommod, 0)

Change in the number of bed in tourist accommodation. Units: bed/Year

accomodation effect=maturity factor*potential accomodat effect

The effect that the new accommodations have on the Fuerteventura attraction factor. Units: Dmnl

active crops=irrigation+active gavias

Area covered by the total active crops. Units: ha

active gav prop=active gavias/MAX GAVIAS

Active gavias proportion. Units: Dmnl

active gavias=INTEG (gavias restoration-abandonment, INIT GAVIAS)

Area covered by active gavias. Units: ha

adjustable runoff=ARC*runoff

Adjustable runoff. Units: m3/Year

AIR=0.18988

Accomodation increase ratio (Source: AC). Units: 1/Year

annual vol gav reuse=reus vol-irrigation reus vol

Annual volumen of reclaimed water for gavias restoration. Units: m3/Year

ARC=0.367

Adjustable runoff constant . Units: Dmnl

artificial land proportion=artificial land/FV area ha

Proportion of modified land. Threshold: 20% sustainability (Graymore et al. 2010). Units: Dmnl

artificial land=roads area+tracks area+nonhoteland+hoteland+golf courses+residential+irrigation

Artificial (modified) land. Units: ha

at landscape indicator=(nat high quality calidad+active gavias)/artificial land

Atraction landscape indicator. Units: Dmnl

available surface water=surface discharge-EVAPORATION+irrigation reus vol

Available surface water. Units: m3/Year

AVERGOODS=1.22027e+009

Average value of the Sea transportation of goods (kg) (Source: ISTAC). Units: kg/Year

AVERSTAY=9.06

Average lenght of the stay (Source: INE). Units: days

B=33.2455

Intercept from regression between births and GDPca. Units: Dmnl

beach m2 2015=beach*scn spill

Beach surface available after 2010. Units: m2

beach m2=IF THEN ELSE(Time<2015,beach,beach m2 2015)

Beach area. Units: m2

beach pc factor=lookup beach pc(i beach pc)

Units: Dmnl

beach pc=beach m2/total population

Available beach per capita. Units: m2/inhab

beach=6.51589e+006

Available beach area (litoral strip of 100m). Units: m2

BIR BASE=-0.018767

Factor from regression between births and GDPca. Units: 1/Year

bir=exp time*GDPca NORMALIZED

Birth rate. Units: 1/Year

births=resident population*bir

Births. Units: inhab/Year

bov demand=n bov*TCONPORC

Water demand by by bovine cattle. Before AS demanda bov=(n bov*TCONBOV). Units: m3/Year

bov rate=-6.83

Change in the number of cows rate. Units: head/Year

bov2012=INTEG (bov rate, 209)

Number of cows after 2012 (for scenarios).Units: head

brine production=(1-SEADES CONVR)*(urban desal demand/SEADES CONVR)

Brine production. Units: m3/Year

built urban=residential+hoteland+nonhoteland+golf courses

Urban built up area. Units: ha

CFBUEU=3.37

Factor of urban built up which affects the houbara habitat. Units: Dmnl

CGc=goat and sheep cattle*Lug

Goat and sheep cattle (expresed as LU). Units: LU

CGcpast=MAX((CGc-potential stocking rate reduction)*NGP,0)

Grazing goat and sheep cattle. Units: LU

CGcpast1=DELAY FIXED (CGcpast, 1, 5120)

Delayed grazing goat and sheep cattle. Units: LU

cgfodproduction=pasture and fodder production/TINGCAPROV

Stocking rate capacity in gavias. Units: head

cgpastac=CGcpast*fac

Goat and sheep cattle which graze in the high quality natural vegetation proportion of the grazeable area. Units: LU

ch aband gavias=abandonment-newirrig-gavias restoration-permanent abandonment

Change in abandoned gavias. Units: ha/Year

ch employ=(tourist employment-delayed employment)/delayed employment

Annual change on the employment. Units: Dmnl

ch hab sec gav=-HCRac*ch aband gavias

Change in the secondary habitat due to changes in the abandoned gavias. Units: ha/Year

ch or=or-1-or-2

Change in the occupancy rate between last year and the previous one. Units: inhab/bed

change HS=loss HSHtracks+loss HSHroads+loss HSHbu+ch hab sec gav-chHSpermabandon

Change in the secondary habitat. Units: ha/Year

change in desalinated water SCNfod=(MAX(total water needs-water total crop,0))*TEXIT

Change in water which will be deslated each year. Units: m3/Year/Year

change nonhot=nonhotel accommodation-delayed nonhot

Change in non hotel accomodations. Units: bed/Year

chGDPca=INTEG (GDPca rate,0)

Change in the GDPca. Units: Dmnl

chHPHpermabandon=HPH prop*HCRpermabandon*permanent abandonment

Houbara Primary Habitat gainance due to the new natural schrub after the permanent abondement. Units: ha/Year

CLIM=0

Climate change scenario activator. Units: Dmnl

CO2 balance=CO2 emission vehicles fleet+CO2 visitors+CO2 ships+CO2balance gavias+CO2balance golf+CO2balance irrigation+CO2balance natural vegetation+Indirect emission of generated waste+Indirect emissions of electricity consumption

Total balance of CO2 in Fuerteventura island. Units: g CO2/Year

CO2 emission vehicles fleet=(demand E transport*DVEF)+(demand E transport*GVEF)

CO2 emissions from vehichles fleet. Units: g CO2/Year

CO2 per capita=CO2 balance/total population

Per capita CO2 emissions. Units: g CO2/(Year*inhab)

CO2 ships=SCO2E*SFCF desglosado*ships

CO2 emissions from ships. Units: g CO2/Year

CO2 transport=CO2 visitors+CO2 ships+CO2 emission vehicles fleet

CO2 from Transport sector. Units: g CO2/Year

CO2 visitors=FCO2E*energy used flights

CO2 emissions related to the energy consumed on flights. Units: g CO2/Year

CO2balance gavias=CO2FACTORgav*(active gavias+(fodder scn area*FPgav))

CO2 factor for gavias. Units: g CO2/Year

CO2balance golf=CO2FACTORgc*golf courses

CO2 factor for golf courses. Units: g CO2/Year

CO2balance irrigation=CO2FACTORirrig*(irrigation+(fp irrig*fodder scn area))

CO2 factor for irrigated areas. Units: g CO2/Year

CO2balance natural vegetation=natural total*NEEevolution

Balance (flow) CO2 emision-sequestration from natural vegetation. Units: g CO2/Year

CO2FACTORgav=-300000

CO2 factor for gavias. Units: g CO2/(Year*ha)

CO2FACTORgc=-6.46e+006

CO2 factor for golf courses. (Source: Muñoz-Rojas et al. 2011). Units: g CO2/(Year*ha)

CO2FACTORirrig=-5e+006

CO2 factor for irrigation. (Source: derived from Muñoz-Rojas et al. 2011). Units: gCO2/(Year*ha)

CPRE=0.0008224

Rainfall coefficient. Units: LU/(ha*mm)

DAYS A YEAR=365

Units: days/Year

deaths=MOR*resident population

Death rate. Units: inhab/Year

deficit hq=IF THEN ELSE(hq area required- nat high quality >0, hq area required- natl high quality vegetation, 0)

Deficit of hectares of high quality natural vegetation required by the grazing needs. Units: ha

degra nthq proportion=degradation hq notrans/(nat hq notrans*OVERGRAZING RATIO)

Degradation of the non transformable high quality natural vegetation proportion. Units: Dmnl

degra thq proportion=degradation hq trans/(nat hq trans*OVERGRAZING RATIO)

Degradation of the transformable high quality natural vegetation proportion. Units: Dmnl

degradation hq notrans=MIN(nthq prop*p deficit hq*OVERGRAZING RATIO,nat hq notrans*OVERGRAZING RATIO)

Degradation of the non transformable high quality natural vegetation caused by overgrazing. Units: ha/Year

degradation hq trans=MIN(thq prop*p deficit hq*OVERGRAZING RATIO,nat hq trans*OVERGRAZING RATIO)

Degradation of the transformable high quality natural vegetation caused by overgrazing. Units: ha/Year

delay beach pc facto=DELAY FIXED (beach pc factor, 1, 1)

Units: Dmnl

delayed employment=DELAY FIXED (tourist employment, 1, REFERENCE EMPLOYMENT)

Units: emp

delayed nonhot=DELAY FIXED (nonhotel accommodation,1,24836.5)

Non hotel accommodation delayed. Units: bed/Year

demand E des=(IF THEN ELSE(Time<2010, TKWM3*urban desal demand , TKWM3*(urban desal demand-desal CORRALEJO)))+requiered energy fodder scn

Electric energy demand for desalination processess. Units: kwh/Year

demand E etp=etp*eecr

Demand of electric energy from the tourist equivalent population. Units: kwh/Year

demand E others=TCEO*pri pop and transp

Demand of electric energy from other sectors. Units: kwh/Year

demand E respop =resident population*eecr

Demand of electric energy from the resident population. Units: kwh/Year

demand E transport=vehicles fleet*TCV

Demand of energy from transportation (by roads). Units: kwh/Year

demand nonel etp=etp*TCNE

Demand of non electric energy from tourist equivalent population. Units:kwh/Year

demand nonel others=TCEOne*pri pop and transp

Demand of non electric energy from other sectors. Units: kwh/Year

demand nonel respop=resident population*TCNE

Demand of non electric energy from resident population. Units: kwh/Year

desal CORRALEJO=1.46e+006

Capacity of the desalination facilities in Corralejo. Units: m3/Year

DVEF=189.6

Diesel vehicles CO2 emission factor. Units: g CO2/kwh

DIST1=316.14

Distance from Gran Canaria by passenger's flights (round trip). Units: km/inhab

DIST2=3234.26

Distance from Madrid by passenger's flights (round trip). Units: km/inhab

DIST3G=6973.66

Distance from Berlin by passenger’s flights (round trip). Units: km/inhab

DIST3UK=5604.92

Distance from London to by passenger’s flights (round trip). Units: km/inhab

DIST4=2291.12

Distance from Puerto de Cádiz to Puerto del Rosario (round trip). Units: km/journey

DOTRPAST=11000

Fodder water requierements. Units: m3/(Year*ha)

ECCG= (LGCC-Egyptian vultures)/LGCC

Egyptian vulture carrying capacity. Units: Dmnl

ECO2E=360

Electricity C02 Emision factor. Units: g CO2/kwh

EECBR=829.495

Population electric energy consumption base ratio, before considering the GPDca effect. Units: kwh/(inhab*Year)

eecr=effect chGDPca*EECBR

Population electric energy consumption Ratio (once the effect of GDPca has been considered). Units: kwh/(inhab*Year)

efec clim=0.9

Coefficient of rainfall for Climate change scenarios. Units: Dmnl

efect reut=(MIN(fodder scn area,potential new active gavias))*TREUG

Effect of the reclaimed water for gavias restoration. Units: ha/Year

effect chGDPca=initial factor evoGDP+chGDPca

Effect of the change in GDPca on energy consumption. Units: Dmnl

effect new built up urb=CFBUEU*new built urban

Effect of the new built up urban on the houbara habitat. Units: ha/Year

effective urban desalinated seawater consumption=MIN(SEADESCAP, urban desal demand

Effective urban desalinated seawater consumption. Removed from the model structure after the OAT. Units: m3/Year

EFLGCC=CGcpast1*Elgcc

Effect of the livestock on the Egyptian vulture carrying capacity. Units: ev

Egyptian vult prop=Egyptian vultures/REF Egyptian vult

Proportion of Egyptian vultures regarding the reference value. Units: Dmnl

Egyptian vultures=INTEG (inc ev-nonat death Ev, 113)

Egyptian vultures population. Units: ev

EICF=2

Energy intensity conversion factor. Units: MJ/km

elec E consum=IF THEN ELSE(SAwr=0, demand E des+demand E others+demand E respop+demand E etp, demand E others+demand E respop+demand E etp)

Total electric energy consumption. Units: kwh/Year

eLGCC=0.0215197

Effect of the livestock over the carrying capacity of the Egyptian vulture (AC). Units: ev/LU

emigration=(resident population*temig)

Emigration rate. Units: inhab/Year

employ index=employ ratio*(NORMAL EMPLOY FACTOR+ch employ)

Employment index. Units: Dmnl

employ ratio=(delayed employment/REFERENCE EMPLOYMENT)

Units: Dmnl

energy losses=IF THEN ELSE(SAef=0, TPPbase, TPPbase+RAMP TPP)

Energy losses for scenarios. Units: Dmnl

energy self sufficient index=(tot prim energy-tot pri no renewab)/tot prim energy

Energy self sufficient index. Units: Dmnl

energy used flights= (DIST1*vis1) + (DIST2*vis2) + (DIST3G*vis3*ratioG) + (DIST3UK*vis3*ratioUK))*EICF

Energy use per passenger (one way flights). Units: MJ/Year

etp=iet*INITIAL ETP

Tourist equivalent population. Units: inhab

EVAPORATION=67000

Annual evaporation rate from water reservoirs. Units: m3/Year

EVTo=(EVTp*pre vol m2)

Evapotranspiration. Units: m/Year

EVTp=0.315

Evapotranspiration (after the improvement of model formulation by means of the SA, the model value is 0.315; before this change, the model value was 0.9). Units: Dmnl

exp time=EXP(B+(BIR BASE*Time))

Units: Dmnl/Year

fac=nat high quality / grazeable area

High quality natural proportion on the total grazeable area. Units: Dmnl

FC pre=0.001

Unit conversor. Units: m/(mm*Year)

FCO2E=69

Flights CO2 Emissions (Source: Becken 2002). Units: g CO2/MJ

FCONV=10000

Unit conversor. Units: m2/ha

filling rate=MIN(73684.2, (reservoir capacity*TEXIT))

Annual filling ratio. Units: m3/Year

FLOWSPRINGR=4.8751e-006

Flow spring ratio. Insensitive parameters. Removing from the model structure after OAT. Units: 1/Year

fod consump bov=TINGCAPROV*n bov

Fodder consumption (and other materials) by bovine cattle. Before AS: TINGBOV*n bov. Units: kg/Year

fod consump porc=TINGCAPROV*n porc

Fodder consumption (and other materials) by pig cattle. Before AS: TINGPORC*n porc. Units: kg/Year

fod importation needs=MAX(requiered fodder caprov-fodder consumption supplied by grazing-Fodder needs grazing potential feedlot cattle feed,0)

Potential fodder importation needs. Units: kg/Year

fod need prop=fodder importation needs/(requiered fodder bovporc+requiered fodder caprov)

Proportion of fodder importantion needs, regarding the total needs. Units: Dmnl

fodder consumption supplied by grazing=TINGCAPROV*(real stocking rate reduction/LUg)*NGP

Fodder consumption supplied by grazing under Measure 3.2. Units: kg/Year

fodder desalinated water supply=INTEG (change in desalinated water SCNfod,0)

Annual capacity of desalination for fodder water supply. Units: m3/Year

fodder importation needs=fod importation needs+requiered fodder bovporc

Fodder importation needs. Units: kg/Year

fodder needs grazing=(CGcpast/LUg*TINGCAPROV)

Fodder needs supplied by grazing. Units: kg/Year

fodder scn area=fod importation needs/FODDER YIELD

Area on the island needed to product all the requiered fodder. Units: ha

FODDER YIELD=37705.5

Annual fodder yield (Source: Palacios et al. 2008). Units: kg/(ha*Year)

fp irrig=1-FPgav

Irrigated fodder area proportion. Units: Dmnl

FPgav=0.4

Non irrigated fodder area proportion (average proportion of the ISTAC serie of data). Units: Dmnl

fst=delay beach pc factor*tpi factor*natural landscape indicator

Tourist attraction index. Units: Dmnl

FUEL CONSs=804.812

Fuel consumption of ships by each kilometer. Units: kg fuel/km

FV area ha=172500

Fuerteventura area (hectares). Units: ha

FV area m=1.725e+009

Fuerteventura area (m2). Units: m2

GAV ABAND INIC=3475.68

Initial value. Units: ha

gavias infiltration=IF THEN ELSE((gavias m2*IR gavias)>(gavias m2*EVTo), (gavias m2*IR gavias)-(gavias m2*EVTo),0)

Annual volume from gavias infiltration. Units: m3/Year

gavias m2=FCONV*active gavias

Unit conversor. Units: m2

gavias restoration=MIN(rehab efec,abandoned gavias*TEXIT)

Restoration of gavias. Units: ha/Year

GCR=0.0515523

Gavias abandonment ratio (AC). Units: 1/Year

GDP effect=GDP NORMAL+GDPreal long*MFACTOR GDP

Effect of the GDP of the most important markets for outbound tourism on the tourist choice of destination index. Units: Dmnl

GDP NORMAL=1

Normalized value of GPD index. Units: Dmnl

GDP real

Annual variation of the GDP from the main markets for outbound tourism for Fuerteventura (Data). Units: Dmnl

GDP2012=0

For scenarios activation. Units: Dmnl

GDPca inmig=GDPca NORMALIZED*MF GDPca INMIG

Effect of the Canarian GDP on immigration processes. Units: Dmnl

GDPca inmig-S= DELAY1(GDPca inmig, TINMIGDPca)

Delayed effect of GDPca on inmigration. Units: Dmnl

GDPca long=IF THEN ELSE(Time<2012, GDPca, GDPca+GDPCAN2012)

Long time series of GDPca. Units: Dmnl

GDPca NORMALIZED=GDP NORMAL+GDPca long

Normalized Canarian GDP. Units: Dmnl

GDPca rate=TI GDPca*TEXIT

Change in GDPca. Units: Dmnl/Year

GDPca

Annual variation of the Canarian GDP (Data). Units: Dmnl

GDPcaFACTOR=4240

Effect of the GDPca on sea transportation of goods. Units: ships

GDPCAN2012=0

For scenarios activation. Units: Dmnl

GDPreal long=IF THEN ELSE(Time<2012, GDP real,GDP real+GDP2012)

Long time series of GDPreal. Units: Dmnl

goat and sheep cattle

Number of heads of goat and sheep cattle until 2011 (Data). Units: head/Year

goatsh demand=goat and sheep cattle*TCONCAPROV

Water demand by by goat and sheep cattle. Units: m3/Year

goatsh2012=INTEG (goatsh rate, 149745)

Number of goats and sheeps after 2012 (for scenarios).Units: head

goatsh rate=-85.83

Change in the number of goats and sheeps rate. Units: head/Year

golf courses dem

Annual golf courses demand (Data). Units: golf course/Year

golf courses=INTEG (nat hq golf+nat lq golf,0)

Source: Aerial photointerpretation from GRAFCAM images. Units: ha

golf gross demand=golf net demand+(golf net demand*GOLFLOSR)

Gross water demand by golf courses irrigation. Units: m3/Year

golf land demand=golf courses dem*SCG

Annual golf land demand. Units: ha/Year

golf net demand=GOLFCONR*golf courses

Net water demand by golf courses irrigation. Units: m3/Year

golf reus vol=TOURISTGOLFREUR*tur treat vol

Reused sewage water volume which is destined to golf courses irrigation. Units: m3/Year

GOLFCONR=10950

Golf courses water consumption. Units: m3/(ha*Year)

GOLFLOSR=0.2

Water loss ratio on golf courses. Units: Dmnl

goods=AVERGOODS-(pasture and fodder production*SAp3)

Average value of the Sea transportation of goods (kg). Units: kg/Year

grazeable area=abandoned gavias+natural total

Units: ha

GROUNDWATER INIT=1.035e+010

Initial value. Units: m3

groundwater=INTEG (gavias infiltration+rainfall recharge+irrigat reinfiltrat-gw pumping-VOL FLOW SEA-vol flow spring,GROUNDWATER INIT)

Groundwater volumen. Units: m3

GVEF=95.312

Gasoline vehicles CO2 emission factor. Units: g CO2/kwh

gw pumping=gwp irrig+gwp livestock+gwp urban+gwp golf

Ground water pumping. Units: m3/Year

gwp golf=IF THEN ELSE(golf gross demand>golf reus vol,golf gross demand-golf reus vol,0)

Ground water pumping for golf courses demand. Units: m3/Year

gwp irrig=IF THEN ELSE(irrigation gross demand>available surface water,irrigation gross demand-available surface water ,0)

Groundwater pumping for irrigation demand. Units: m3/Year

gwp livestock=bov demand+goatsh demand+porc demand

Groundwater pumping for livestock demand. Units: m3/Year

gwp rpop=rpop gross demand *RPOPAQUIFR

Groundwater pumping for resident population demand. Units: m3/Year

gwp urban=gwp rpop

Groundwater pumping for urban demand. Units: m3/Year

ha roads=new roads*RATIO ha km ROADS

Roads area (in hectares). Units: ha/Year

ha tracks=new tracks*RATIO ha km TRACKS

Tracks area (in hectares). Units: ha/Year

HCRac=0.966

Houbara habitat change ratio due to active crops. Units: Dmnl

HCRpermabandon=0.178

Houbara habitat change ratio due to permanent abandonment of gavias. Units: Dmnl

HCRroads=15.509

Houbara habitat change ratio due to roads. Units: ha/km

HCRtracks=8.42

Houbara habitat change ratio due to tracks. Units: ha/km

HCRub=0.119

Houbara habitat change ratio per hectare of new urban built up. Units: Dmnl

high quality degradation=degra nthq proportion+degra thq proportion

Degradation of the total high quality natural vegetation proportion. Units: Dmnl

hm3 recharge=tot recharge/hm3

Recharge (hm3). Units: hm3/Year

hm3=1e+006

Unit conversor. Units: m3/hm3

hot land demand=MAX(0,hotel accommod demand*HOTEL ACCOMMODATION LAND DEM)

Hotel land demand. Units: ha/Year

hotel accommod demand=accommodation ch-change nonhot

Hotel accommodation demand. Units: bed/Year

HOTEL ACCOMMODATION LAND DEM=0.0059

Demand of land by each nonhotel accommodation bed (Source: Government of Canary Island 2004). Units: ha/bed

hoteland=INTEG (nat hq hot+nat lq hot,60.9612)

Units: ha

Houb Habitat prop=total houbara habitat/REF houb habitat

Houbara habitat proportion. Units: Dmnl

HPH prop=primary habitat/total houbara habitat

Proportion of the primary habitat regarding the total houbara habitat. Units: Dmnl

HPHinicial=11051

Initial value. Units: ha

HPHLRntracks=HPH prop*HCRtracks

Houbara Primary Habitat loss Ratio per km of tracks. Units: ha/km

HPHLRroads=HPH prop*HCRroads

Houbara Primary Habitat loss Ratio per km of roads. Units: ha/km

hq area required=cgpastac/stocking rate max

High quality natural vegetation area required by the grazing needs. Units: ha

HSH prop=secondary habitat/total houbara habitat

Proportion of the primary habitat regarding the total houbara habitat. Units: Dmnl

HSHinicial=19003.3

Initial value. Units: ha

HSHLRntracks=HSH prop*HCRtracks

Houbara Secondary Habitat loss Ratio per km of tracks. Units: ha/km

HSHLRroads=HCRroads*HSH prop

Houbara Secondary Habitat loss Ratio per km of roads. Units: ha/km

i beach pc=beach pc/NBEACH THRESHOLD

Beach pc Index used in order to normalized the dimmension. Units: Dmnl

ICR=0.00110302

Irrigation change rate (AC). Units: 1/Year

iet=IF THEN ELSE(Time<1997,1+RAMP(-0.201,1996,1997),fst*GDP effect*SHOCKS*accomodation effect*MFACTOR IET)

Tourist choice of destination index. Units: Dmnl

inc ev=MIR*Egyptian vultures*ECCG

Increase on the Egyptian vulture population. Units: ev/Year

inc pobres=respop delay-pobres ret-1

Change in resident population. Units: inhab

inc pop=total population-pobtot ret

Annual increase of population. Units: inhab

Indirect emission of generated waste=USW generation*WCO2E

Indirect emission of generated waste. Units: g CO2/Year

Indirect emissions of electricity consumption=Consumo E elect*ECO2E

Indirect emissions of electricity consumption. Units: g CO2/Year

INIT GAVIAS=324.318

Initial value. Units: ha

INIT IRRIG=359

Initial value. Units: ha

INIT RC=2.08421e+006

Initial reservoir capacity. Units: m3

INITIAL ETP=23735

Initial tourist equivalent population. Units: inhab

INITIAL factor evoGDP=1

Initial value. Units: Dmnl

INITIAL INMIG=7608

Initial value. Units: inhab/Year

inmigration=IF THEN ELSE(Time<1997,INITIAL INMIG, INITIAL INMIG*employ index*"GDPca inmig-S")

Immigration rate. Units: inhab/Year

IR gavias=0.2

Infiltration ratio in gavias. Units: m/Year

IR=0.062

Infiltration ratio from rainfall. Units: Dmnl

IRCONR=7000

Irrigation consumption ratio. Units: m3/(ha*Year)

IRLOSR=0.43

Irrigation loss ratio. Units: Dmnl

irrigat reinfiltrat=irrigation gross demand-irrigation net demand

Infiltration water volume from irrigation. Units: m3/Year

irrigation gross demand=irrigation net demand+(irrigation net demand*IRLOSR)

Gross demand for irrigation. Units: m3/Year

irrigation net demand=irrigation*IRCONR

Net demand for irrigation. Units: m3/Year

irrigation reus vol=reus vol*IRRIGREUSR

Reused irrigation water volume. Units: m3/Year

irrigation=INTEG (newirrig, INIT IRRIG)

Irrigated area. Units: ha

IRRIGREUSR=0

Irrigation water reused ratio. Units: Dmnl

ISLAND=0.18

Proportion of tourist arrived from other island of the Archipelago. Units: Dmnl

Kc=0.35

Cereal coefficient. Insensitive parameters. Removing from the model structure after OAT. Units: Dmnl

km2=0.01

Change of units. Units: km2

Kn=23.5334

Egyptian vulture population carrying capacity natural, without considering the livestock effect. Units: ev

kwh flights=energy used flights*UDkwh MJ

Primary energy (kwh/y) from flights. Units: kwh/Year

kwh ships=SFCF desglosado*ships*UD kg fuel MJ*UDkwh MJ

Fuel used by ships. Units: kwh/Year

landscape indicator=(nat high quality +active gavias)/artificial land

Landscape indicator. Units: Dmnl

LGCC=EFLGCC+Kn

Increas on the Egyptian vulture carriying capacity because of the effect of livestock. Units: ev

lookup beach pc=([(0,0)-(100,1)],(0,0.1),(0.13333,0.2),(0.2,0.5),(1,1))

Source: Different scientific literature and expert (pers. com). Units: Dmnl

loss HP=loss HPHtracks+loss HPHroads+loss HPHbu-chHPHpermabandon

Change in the primary habitat. Units: ha/Year

loss HPHbu=effect new built up urb*HCRub*HPH prop

Houbara Primary Habitat Loss due to built urban. Units: ha/Year

loss HPHroads=new roads*HPHLRroads

Loss on the primary habitat due to the construction of roads. Units: ha/Year

loss HPHtracks=new tracks*HPHLRntracks

Loss on the primary habitat due to the construction of tracks. Units: ha/Year

loss HSHbu=effect new built up urb*HCRub*HSH prop

Loss on the secondary habitat due to urban areas.Units: ha/Year

loss HSHroads=new roads*HSHLRroads

Loss on the secondary habitat due to the construction of roads. Units: ha/Year

loss HSHtracks=new tracks*HSHLRntracks

Loss on the secondary habitat due to the construction of roads. Units: ha/Year

loss water rpop=rpop net demand*LOSS

Losses in water consumption by resident population. Units: m3/Year

loss water tur=tur net demand*LOSS

Losses in water consumption by tourist population. Units: m3/Year

LOSS=0.31

Loss ratio for urban water supply. Units: Dmnl

LUg=0.15

Livestock unit factor (1 goat= 0.15 LU). Units: LU/head

maturity factor=IF THEN ELSE(rem new accommod>=MATURITY THRESHOLD, MAX MATURITY FACTOR, rem new accommod/MATURITY THRESHOLD)

Maturity factor. Units: Dmnl

MATURITY THRESHOLD=0.1

Maturity threshold. For scenario simulation. Units: Dmnl

MAX ACCOMMODATION=133000

Maximum number of beds. Units: bed

MAX GAVIAS=800

Historical maximun of gavias area (Perdomo). Units: ha

MAX MATURITY FACTOR=1

Units: Dmnl

MF GDPca INMIG=1.24816

Effect of the GDPca on immigration (AC). Units: Dmnl

MFACTOR GDP=3.14604

Effect of the GDPreal on foreign tourists arrivals (AC). Units: Dmnl

MFACTOR IET=0.704086

Factor on the tourist choice index (AC). Units: Dmnl

MIR=0.609399

Maximum or intrinsic growth ratio for the Egyptian vulture (AC). Units: 1/Year

MOR=0.0036523

Mortality ratio. Units: 1/Year

n bov

Number of bovine heads until 2011 (Data). Units: head/Year

n bov2025=IF THEN ELSE(Time<2012, n bov,bov2012)

Number of cows until 2025 (for scenarios). Units: head

n goatsh 2025=IF THEN ELSE(Time<2012, goat and sheep cattle, goatsh2012)

Number of goats and sheeps until 2025 (for scenarios). Units: head

n porc

Number of porcine heads until 2011 (Data). Units: head/Year

n porc2025=IF THEN ELSE(Time<2012, n porc, porcino2012)

Number of pigs until 2025 (for scenarios). Units: head

nat high quality=nat hq notrans+nat hq trans

Total high quality vegetation. Units: ha

nat hq golf=golf land demand*nat1

Change rate: from transformable high quality natural to golf. Units: ha/Year

nat hq hot=hot land demand*nat1

Change rate: from transformable high quality natural to hotel accommodations. Units: ha/Year

nat hq nonhot=nonhot land demand*nat1

Change rate: from transformable high quality natural to nonhotel accommodations. Units: ha/Year

nat hq notrans=INTEG (recovery nthq-degradation hq notrans,NATHQNTIN)

Area occupied by high quality vegetation (protected, so non transformable). Units: ha

nat hq prop=nat high quality /natural total

Units: Dmnl

nat hq res=res land demand*nat1

Change rate: from transformable high quality natural to residential. Units: ha/Year

nat hq roads=nat1*ha roads

Change from high quality transformable to roads rate. Units: ha/Year

nat hq tracks=ha tracks*nat1

Change from high quality transformable to tracks rate. Units: ha/Year

nat hq trans=INTEG (recovery thq-degradation hq trans-nat hq nonhot-nat hq golf-nat hq hot-nat hq res-nat hq tracks-nat hq roads,NATHQTIN)

Area occupied by high quality vegetation (transformable, so non protected). Units: ha

nat lq golf=golf land demand*nat2

Change rate: from transformable low quality natural to golf courses. Units: ha/Year

nat lq hot=hot land demand*nat2

Change rate: from transformable low quality natural to hotel accommodations. Units: ha/Year

nat lq nonhot=nonhot land demand*nat2

Change rate: from transformable low quality natural to nonhotel accommodations. Units: ha/Year

nat lq res=res land demand*nat2

Change rate: from transformable low quality natural to residential. Units: ha/Year

nat lq roads=ha roads*nat2

Change from low quality transformable to roads rate. Units: ha/Year

nat lq tracks=ha tracks*nat2

Change from low quality transformable to tracks rate. Units: ha/Year

nat lq=INTEG (permanent abandonment+degradation hq notrans+degradation hq trans-nat lq nonhot-nat lq golf-nat lq hot-nat lq res-recovery nthq-recovery thq-nat lq roads-nat lq tracks,NATLQIN)

Area occupied by low quality vegetation (actual vegetation). Units: ha

nat1=nat hq trans/natural trans

Proportion of the transformable high quality natural vegetation respect to the total transformable natural vegetation. Units: Dmnl

nat2=nat lq/natural trans

Proportion of the low quality natural vegetation respect to the total transformable natural vegetation. Units: Dmnl

NATACIN=NATHQNTIN+NATHQTIN

Initial value. Units: ha

NATHQNTIN=11529.9

Initial value. Units: ha

NATHQTIN=4143.07

Initial value. Units: ha

NATIN=153763

Initial value of the total natural vegetation. Units: ha

NATLQIN=138089

Initial value. Units: ha

natural landscape indicator=natural total/NATIN

Indicator of the naturality of the landscape. Units: Dmnl

natural total=nat high quality+nat lq

Area covered by natural vegetation. Units: ha

natural trans=nat hq trans+nat lq

All the transformable natural vegetation. Units: ha

NBEACH THRESHOLD=30

Normalized beach factor threshold (PTEOTIF, 2007). Units: m2/inhab

NEEevolution=(NEEfactor+preFACTOR*LN(rainfall))

NEE evolution derives from a linear regresion from literature review. Units: gCO2/(Year*ha)

NEEfactor=1.13987e+007

Net ecosystem exchange factor. Units: g CO2/(Year*ha)

net migration rate=(inmigration-emigration)/(inmigration+emigration)

Net migration indicator. Units: Dmnl

new built urban=nat hq nonhot+nat hq golf+nat hq hot+nat hq res+nat lq nonhot+nat lq golf+nat lq hot+nat lq res

New built up urban. Units: ha/Year

new built urban=nat hq nonhot+nat hq golf+nat hq hot+nat hq res+nat lq nonhot+nat lq golf+nat lq hot+nat lq res

New built up urban. Units: ha/Year

new roads=MAX(0, ROADSn*inc pop)

New roads demand. Units: km/Year

new tracks=MAX(0, inc pobres*TRACKSn)

New tracks demand. Units: km/Year

newirrig=abandoned gavias*ICR

Transformation of abandoned gavias into new irrigated lands. Units: ha/Year

NGP=0.5

Net grazing proportion. Units: Dmnl

no tend=0

For scenarios implementation. Units: Dmnl

nonat death Ev=real electrocution+poisoning

Non natural deaths of Egyptian vultures (poisoning and other non natural causes). Units: ev/Year

NONHOT ACCOM RATIO=0.53

Nonhotel accommodations ratio regarding the total tourist accommodation (Source: ISTAC 2012). Units: 1/Year

nonhot land demand=MAX(0,change nonhot*NONHOTEL ACCOMMODATION LAND DEM)

Units: ha/Year

NONHOTEL ACCOMMODATION LAND DEM=0.0042

Demand of land by each nonhotel accommodation bed. Units: ha/bed

nonhotel accommodation=tourist accommodation capacity*NONHOT ACCOM RATIO

Non hotel accommodation capacity. Units: bed/Year

nonhoteland=INTEG (nat hq nonhot+nat lq nonhot, 86.9242)

Units: ha

NORMAL EMPLOY FACTOR=1

When there are no changes in the employment, the index will be the normal value. Units: Dmnl

NOTOURIST EMPLOY=0.249

Proportion of employment not linked to tourist. Insensitive parameter. Removing from the model structure after OAT. Units: Dmnl

nthq prop=nat hq notrans/nat high quality

Proportion of the non transformable high quality natural vegetation respect to the total high quality natural vegetation. Units: Dmnl

occupancy rate=etp/tourist accommodation capacity

Tourist occupancy rate. Units: inhab/bed

or-1=DELAY FIXED (occupancy rate, 1, 0.68)

Delay in the occupancy ratio. Units: inhab/bed

or-2=DELAY FIXED (occupancy rate, 2, 0.7)

Delay of 2 years in the occupancy ratio. Units: inhab/bed

overgrazing indicator=(CGcpast/ grazeable area)/stocking rate max

Overgrazing indicator. Units: Dmnl

OVERGRAZING RATIO=1

Time unit. Units: 1/Year

p deficit hq=DELAY1(deficit hq, TES)

Effect of the deficit of hectares of high quality natural vegetation required by the grazing needs in the time. Units: ha

pasture and fodder production=FODDER YIELD*productive gavias

Units: kg/Year

peg=IF THEN ELSE(PGG=1,PEGcpl,PEGspl)

Probability of electrocution. Units: 1/(km*Year)

PEGcpl=2.425e-005

Probability of electrocution with corrective measures in power lines. Units: 1/(km*Year)

PEGspl=9.7e-005

Probability of electrocution without corrective measures in power lines. Units: 1/(km*Year)

PENINSULA=0.078

Proportion of tourist arrived from the Iberian Peninsula. Units: Dmnl

permanent abandonment=abandoned gavias/ST

Permanent abandonment (from abandoned gavias). Units: ha/Year

pg reus vol=tur treat vol-golf reus vol

Reuse water volumen destined to irrigation of parks and gardens. Units: m3/Year

PGG=STEP(1, 2006)

Corrective measures plan agains electrocution. Units: Dmnl

Photovoltaic energy

Data. Units: kwh/Year

pig rate=344.5

Change in the number of pigs rate. Units: head/Year

pimary E others=demand E others*energy losses

Primary energy demand from other sectors. Units: kwh/Year

plan rehab

Rehabilitation Plan (Data). Units: ha/Year

pli=resident population*PLRpc

Length of power lines. Units: km

PLRpc=0.00335

Power lines Ratio per capita. Units: km/inhab

pobres ret-1=DELAY FIXED (respop delay, 1, 41477)

Delayed resident population (in 1994). Units: inhab

POBRESINIT=42938

Initial value. Units: inhab

poisoning

Egyptian vultures deaths caused by poisoning (Data). Units: ev/Year

pop density=total population/FV area ha

Population density indicator. Units: inhab/ha

porc demand=n porc*TCONPORC

Water demand by by porcine cattle. Units: m3/Year

porcine2012=INTEG (pig rate, 6636)

Number of pigs after 2012 (for scenarios).Units: head

pot emigration=(resident population*TEXIT)*NOTOURIST EMPLOY

Potential emigration. Units: inhab/Year

potential accomodat effect=tourist accommodation capacity/REFERENCE ACCOMMOD

Units: Dmnl

potential electrocution=peg*pli*Egyptian vultures

Number of potential Egyptian vultures died by electrocution. Units: ev/Year

potential feedlot cattle feed=MAX(pasture and fodder production-fodder consumption supplied by grazing,0)

Potential feedlot cattle feeding. Units: kg/Year

potential new active gavias=IF THEN ELSE(productive gavias<active gavias, 0, MAX(riegavmax-active gavias,0))

Potential restored gavias. Units: ha

potential stocking rate reduction=IF THEN ELSE(SAp32=0, 0, cgfodproduction*LUg)

Potential stocking rate reduction thanks to measures implementation. Units: LU

pre mm

Rainfall (mm). Data. Units: mm

pre vol m2=FC pre*rainfall

Rainfall (m2). Units: m/Year

pre vol=pre vol m2*FV sur m

Annual rainfall (m3/year). Units: m3/Year

pre2011=pre mm

Rainfall until 2011. Units: mm

pre2012=IF THEN ELSE(CLIM=0, pre mm, pre mm*efec clim)

Rainfall after 2011 (for scenarios). Units: mm

preFACTOR=-2.25604e+006

Rainfall factor on the NEE. Units: (g CO2)/(Year*ha*mm)

pri energy navegation=(kwh flights+kwh ships)*TPP

Primary energy from navegation (flights and ships). Units: kwh/Year

pri energy transport=demand E transport*TPP

Primary energy from transportation (by road). Units: kwh/Year

pri nonel etp=demand nonel etp*TPP

Primary non electric energy from tourist equivalent population. Units: kwh/Year

pri nonel others=demand nonel others*TPP

Primary non electric energy from tourist equivalent population. Units: kwh/Year

pri nonel respop=demand nonel respop*TPP

Primary non electric energy from resident population. Units: kwh/Year

pri pop and transp=pri tot population+pri energy transport

Total primary energy from the population and transportation. Units: kwh/Year

pri tot others=pimary E others+pri nonel others

Total primary energy from other sectors. Units: kwh/Year

pri tot population=primary E respop+pri nonel respop+primary E etp+pri nonel etp

Total primary energy from the population. Units: kwh/Year

primary E desalation=demand E des*energy losses

Primary energy demand for desalination processess. Units: kwh/Year

primary E etp=demand E etp*energy losses

Primary energy from tourist equivalent population. Units: kwh/Year

primary E respop=demand E respop*energy losses

Primary energy from resident population. Units: kwh/Year

primary habitat=INTEG (-loss HP, HPHinicial)

Primary habitat of the houbara. Units: ha

productive gavias=MIN(active gavias,riegavmax)

Productive gavias. Units: ha

ptotFACTOR=0.0003261

Effect of the total population on the ship navigation. Units: ships/inhab

rainfall recharge=pre vol*IR

Groundwater recharge from rainfall. Units: m3/Year

rainfall=IF THEN ELSE(Time<2012, pre2011,pre2012)

Rainfall (long serie). Units: mm

Ratio between tourist accommodation and resident population=(tourist accommodation capacity/resident population)*100

Ratio between tourist accommodation and resident population. Units: bed/inhab

RATIO ha km ROADS=1

Roads width (10 m). Units: ha/km

RATIO ha km TRACKS=0.4

Tracks width (4 m). Units: ha/km

ratioG=0.61

Proportion of German tourist from the total foreing tourists arrived to Fuerteventura. Units: Dmnl

ratioUK=0.38

Proportion of German tourist from the total foreing tourists arrived to Fuerteventura. Units: Dmnl

real electrocution=potential electrocution+RANDOM NORMAL(0,6, 0, 1,7)

Number of real Egyptian vultures died by electrocution. Units: ev/Year

real stocking rate reduction=MIN(CGc,potential stocking rate reduction)

Real stocking rate reduction. Units: LU

recovery nthq=(nat lq/RT)*nthq prop

Recovery rate to non transformable high quality natural vegetation. Units: ha/Year

recovery thq=(nat lq/RT)*thq prop

Recovery rate to transformable high quality natural vegetation. Units: ha/Year

recup gavia reu=0

For scenarios implementation. Units: Dmnl

recycled waste=waste mixed*TRECRES

Extracted wastes from the mix to be recycled. Units: kg/Year

reduction of grazing=potential stocking rate reduction/LUg*TINGCAPROV

Reduction of consumption removed of the grazing. Units: kg/Year

REF Egyptian vult=190

Reference value in 2009 (Source: Mallo and Díez 2010). Units: ev

REF houb habitat=29633

Reference data (2002). Units: ha

REFERENCE ACCOMOD=30379

Reference value (in this case, the initial value). Units: bed

REFERENCE EMPLOYMENT=8549

Reference value. Units: emp

rehab efec=IF THEN ELSE(Time<2011,plan rehab, rehab2011)

Rehabilitation effect. Units: ha/Year

rehab2011=SAgr*efect reut

Gavias rehabilitation from 2011, for scenarios implementation. Units: ha/Year

rem new accommod=(MAX ACCOMMODATION-tourist accommodation capacity)/(MAX ACCOMMODATION)

Remanents new accommodation beds. Units: Dmnl

renewable E production=IF THEN ELSE(SAwr=0,TI Eeolica+Photovoltaic energy+Thermal energy, Wind energy+Photovoltaic energy+Thermal energy+demand E des)

Renewable energy production. Units: kwh/Year

requiered energy fodder scn=fodder desalinated water supply*TKWM3

Requiered energy to supply the desalinated water demand for fodder scenario. Units: kwh/Year

requiered fodder bovporc=fod consump porc+fod consump bov

Total requiered fodder for cattle herd (cow+ pig). Units: kg/Year

requiered fodder caprov=TINGCAPROV*goat and sheep cattle

Fodder consumption (and other materials) by goat and sheep cattle. Units: kg/Year

RErpop=RAMP(-0.31, 2012, 2025)

For scenario analysis. Recession efect on water consumption of resident population (the proportion of decrease between 2008-2011). Units: m3/(Year*inhab)

res land demand=MAX(inc pobres*TSUCVOpc, 0)

Residential and other uses land demand. Units: ha/Year

reservoir capacity=INTEG (-filling rate,INIT RC)

Reservoir capacity. Units: m3

resident population=INTEG (inmigration+births-deaths-emigration, POBRESINIT)

Units: inhab

residential=INTEG (nat hq res+nat lq res,2465.33)

Area occupied by residential uses. Units: ha

respop delay=DELAY FIXED (resident population,1,42882)

Resident population one year delayed (in 1995: 42882 inhabitants). Units: inhab

respop treat vol=RPTREATMENTP*rpop sewage vol

Treated water from resident population sewage water. Units: m3/Year

reus vol=REUSR*respop treat vol

Volume of reusing urban reclaimed water. Units: m3/Year

REUSR=0.35

Ratio of reusing urban reclaimed water. Units: Dmnl

riegavmax=water total crop/DOTRPAST

Maximun active gavias area that we can irrigate with the available water. Units: ha

road network density=(roads/(FV sur ha*km2))

Road network density. Units: km/km2

roads area= INTEG (nat hq roads+nat lq roads,ROADSin)

Area occupied by roads. Units: ha

roads=(roads area)/RATIO ha km ROADS

Length of roads. Units: km

ROADSin=423.205

Initial value. Units: ha

ROADSn=0.000358

New roads demand ratio. Units: km/inhab/Year

rpop desal demand=rpop gross demand*RPOP DESAL DEM

Desalinated water demand by resident population. Units: m3/Year

rpop desal gw ratio=TOT DEMAND-RPOPAQUIFR

Residential population desalinated water demand ratio. Units: Dmnl

rpop gross demand=loss water rpop+rpop net demand

Gross water demand by resident population. Units: m3/Year

rpop net demand=resident population*rpopconr

Net water demand by resident population. Units: m3/Year

rpop sewage vol=rpop net demand*RPSEWAGEPROP

Residential population sewage water volume. Units: m3/Year

RPOPAQUIFR=0.01

Population Water demand from the aquifer (ratio). Units: Dmnl

rpopconr= IF THEN ELSE(SAer=0, RPOPCONRbase,RPOPCONRbase+RErpop)

Residential population water consumption. Units: m3/(inhab*Year)

RPOPCONRbase=65.7

Residential population water consumption ratio. Units: m3/(Year*inhab)

RPSEWAGEPROP=0.6

Sewage proportion. Units: Dmnl

RPTREATMENTP=0.91

Treatment water proportion from resident population. Units: Dmnl

RT=136.754

Average time of plant composition recovery. Units: Year

runoff=RUNOFFcte*pre vol

Annual runoff volume. Units: m3/Year

RUNOFFcte=0.026

Runoff factor. Units: Dmnl

SAer=0

Scenario activator (economic recession). Units: Dmnl

SAfod=0

Scenario fodder production on the island activator. Units: Dmnl

SAgr=0

Scenario gavias reuse activator. Units: Dmnl

SAp3=IF THEN ELSE(SAfod=1, SAfod, SAgr)

Scenario Activator for measure M.3. Units: Dmnl

SAp32=0

Scenario activator for Measure 3.2. Units: Dmnl

SAwr=0

Scenario Activator: renowable production of desalinated water. Units: Dmnl

SCG=44

Area occupied by each golf course. Units: ha/golf course

scn spill=1-spill*STEP(1,2015)+spill*0.1111*RAMP(0.1, 2018,2025)

Units: Dmnl

SCO2E=3200

Ships CO2 Emission Factor. Units: g CO2/kg fuel

SEADES CONVR=0.45

Seawater desalination conversion ratio (Source: Meerganz von Medeazza et al. 2007; Pérez-González et al. 2012). Units: Dmnl

SEADESCAP=2.757e+007

Seawater desalination capacity. Insensitive parameters. Removed from the model structure after OAT. Units: m3/Year

secondary habitat=INTEG (-change HS, HSHinicial)

Secondary habitat of the houbara. Units: ha

selective waste collection=total population*TRECSELEC

Selective collection of the urban solid waste. Units: kg/Year

SEWAGE PROP TUR=0.57

Proportion of sewage water from tourist consumption (Source: CIAGC 2011). Units: Dmnl

SFACTOR=691.1

Ships factor. Intercept ships. By linear regression. Units: ships

SFCF desglosado=FUEL CONSs*DIST4*(goods/shipCAPACITY)

Units: kg fuel/(Year*ships)

share of renewable energy=energy self sufficient index*100

Share of renewable energy. Units: Dmnl

shipCAPACITY=2.56617e+009

Carriying capacity at 55% of the GT. Units: kg/ships

ships=SFACTOR+GDPcaFACTOR*GDPca long+ptotFACTOR*total population

Units: ships

SHOCK ARAB SPRING=RAMP(0.11, 2010 , 2011)+RAMP(-0.0367, 2011, 2014)

Arab Spring effect (Canalis 2013). Units: Dmnl

SHOCK NORMAL=1

Normalised shock. Units: Dmnl

SHOCKS=SHOCK NORMAL+SHOCK ARAB SPRING

Benchmarks. Units: Dmnl

spill=0

For future scnearios of a spill. Units: Dmnl

ST=79

Period of succession after the abandonment of agricultural areas. Units: Year

stocking rate max=CPRE*rainfall

Maximum stocking rate capacity. Units: LU/ha

surface discharge=IF THEN ELSE((surface water*TEXIT)<irrigation gross demand, (surface water*TEXIT), irrigation gross demand)

Surface discharge. Units: m3/Year

surface recharge=IF THEN ELSE(adjustable runoff<(reservoir capacity*TEXIT), adjustable runoff, (reservoir capacity*TEXIT))

Surface recharge. Units: m3/Year

SURFACE WATER INIT=2.6e+006

Initial value. Units: m3

surface water=INTEG (surface recharge-surface discharge,SURFACE WATER INIT)

Surface water volume. Units: m3

TCEO=0.254

Electric energy consumption ratio by other sectors. Units: Dmnl

TCEOne=0.27

Non electric energy consumption ratio by other sectors. Units: Dmnl

TCNE=333.302

Non electric consumption ratio by resident population. Units: kwh/(inhab*Year)

TCONBOV=17.3

Water consumption by each head of livestock (cows). Insensitive parameters. Removing from the model structure after OAT. Units: m3/head

TCONCAPROV=1.825

Water consumption by each head of livestock (goats and sheeps). Units: m3/head

TCONPORC=2.87

Water consumption by each head of livestock (pigs). Units: m3/head

TCV=13816.1

Annual energy consumption ratio by each car. Units: kwh/(car*Year)

TEMIG BASE=0.084

Base emigration ratio. Units: 1/Year

temig=TEMIG BASE/employ index

Units: 1/Year

TER=0.36+RAMP(-0.06, 2009, 2010)

Touristic employment ratio.Units: emp/inhab

TES=6.40479

Time to detect the overgrazing effects (AC). Units: Year

TEXIT=1

Unit conversor. Units: 1/Year

TGEREURBpc=589.28

Urban waste generation per capita. Units: kg/(inhab*Year)

Thermal energy

Data. Units: kwh/Year

thq prop=nat hq trans/ nat high quality

Proportion of the transformable high quality natural vegetation respect to the total high quality natural vegetation. Units: Dmnl

THRESHOLD OR=0.530499

Profitability threshold for the occupancy rate.Units: inhab/bed

TINGBOV=16607.5

Fodder consumption by each head of livestock (cows). Insensitive parameters. Removing from the model structure after OAT. Units: kg/(head*Year)

TINGCAPROV=657

Fodder consumption by each head of livestock (goats and sheeps). Units: kg/(head*Year)

TINGPORC=1124.2

Fodder consumption by each head of livestock (pigs). Insensitive parameters. Removing from the model structure after OAT. Units: kg/(head*Year)

TINMIGDPca=2

Time of the effect of the GDPca on the inmigration (AC).Units: Year

TKWM3=4.5

Energy consumption for desalation. Units: kwh/m3

TKWM3=4.5

Energy consumption for desalation. Units: kwh/m3

tmot=effect chGDPca*TMOTN

Motorization index. Units: car/inhab

TMOTN=0.421658

Motorization index base (AC). Units: car/inhab

TOT DEMAND=1

Total water demand. Units: Dmnl

tot pri no renewab=tot prim energy-renewable E production

Total primary non renewable energy. Units: kwh/Year

tot prim energy=pri tot others+pri tot population+pri energy transport+primary E desalation+pri energy navigation

Total primary energy demand. Units: kwh/Year

tot recharge=gavias infiltration+irrigat reinfiltrat+rainfall recharge

The average recharge. Units: m3/Year

tot reus vol=golf reus vol+reus vol+pg reus vol

Total volume of reusing urban reclaimed water. Units: m3/Year

tot sewage vol=tur treat vol+respop treat vol

Total population sewage water volume. Units: m3/Year

total houbara habitat=primary habitat+secondary habitat

Total habitat of the houbara. Units: ha

total population=resident population+etp

Units: inhab

total water needs=DOTRPAST*SAfod*(fodder scn area+productive gavias)

Total water needs. Units: m3/Year

totEpri pc=tot prim energy/total population

Total primary energy per capita. Units: kwh/(Year*inhab)

tourist accommodation capacity=INTEG (accomodation ch,REFERENCE ACCOMOD)

Tourist accomodation capacity.Units: bed

tourist employment=etp*TER

Tourist employment.Units: emp

tourist price index

Tourist price index (Data). Units: Dmnl

TOURISTGOLFREUR=RAMP(0.6, 2002, 2003)

Reusing ratio of tourist recalimed water on golf courses. Units: Dmnl

tpi factor=tpi NORMAL-TPI long

Tourist prices index factor. Units: Dmnl

TPI long=IF THEN ELSE(Time<2012, tourist price index,tourist price index+TPI2012)

Long time series of TPI. Units: Dmnl

tpi NORMAL=1

Normalized tourist price index. Units: Dmnl

TPI2012=0

For scenarios activation. Units: Dmnl

TPP=1

Non electric energy loss ratio (from primary energy to final energy (Source: Government of Canary Islands 2006). Units: Dmnl

TRACKin=471.96

Initial value. Units: ha

tracks area=INTEG (nat hq tracks+nat lq tracks,TRACKin)

Area occupied by tracks. Units: ha

tracks=(tracks area)/RATIO ha km TRACKS

Length of tracks. Units: km

TRACKSn=0.001719

New tracks demand ratio. Units: km/(Year*inhab)

treated sewage proportion=tot sewage vol/urb sewage vol

Treated sewage proportion. Units: Dmnl

TRECRES=0.07

Recycled waste ratio from the mixture of waste. Units: Dmnl

TRECSELEC=49.57

Selective urban solid wastes collection ratio. Units: kg/(Year*inhab)

TREUG=0.2

Annual ratio for gavias recuperation. Units: 1/Year

TSUCVOpc=0.0743173

Built Urban and other uses per house ratio (AC). Units: ha/(inhab*Year)

tur gross demand=loss water tur+tur net demand

Gross water demand by tourist population. Units: m3/Year

tur net demand=etp*TURCONR

Net water demand by tourist population. Units: m3/Year

tur sewage vol=tur net demand*SEWAGE PROP TUR

Tourist sewage water volume. Units: m3/Year

tur treat vol=tur sewage vol*TUR TREAT

Treated water from tourist population sewage water. Units: m3/Year

TUR TREAT=1

Tourist water retreat ratio. Units: Dmnl

TURCONR=126.02

Tourist water consumption ratio. Units: m3/(inhab*Year)

tures=etp/resident population

Ratio of tourists to residents. Units: Dmnl

UD kg fuel MJ=40.5

Units change. Units: MJ/kg fuel

UDkwh MJ=0.277

Units change. Units: kwh/MJ

urb sewage vol=tur sewage vol+rpop sewage vol

Urban sewage water volume. Units: m3/Year

urban desal demand=rpop desal demand+tur gross demand

Urban desalination water demand. Units: m3/Year

urban gross demand=rpop gross demand+tur gross demand

Gross water demand by the population. Units: m3/Year

USW generation=total population*TGEREURBpc

Urban solid waste generation. Units: kg/Year

vehicles fleet=total population*tmot

Vehicles fleet. Units: car

vis1=ISLAND*visitors

Passengers arrived from other islands of the Canarian Archipielago. Units: inhab/Year

vis2=PENINSULA*visitors

Passengers arrived from the Iberian Peninsula. Units: inhab/Year

vis3=ABROAD*visitors

Passengers arrived from foreing countries. Units: inhab/Year

visitors=(etp/AVERSTAY)*DAYS A YEAR

Number of visitors arrived to Fuerteventura Island. Units: inhab/Year

VOL FLOW SEA=9e+006

Volume flowing into sea. Units: m3/Year

vol flow spring=50457.6

Volume flowing through spring. Before SA= groundwater*FLOWSPRINGR. Units: m3/Year

vol max reu=active gavias*DOTRPAST

Potential water volumen requiered by gavias. Units: m3/Year

waste managed in landfills=waste mixed-recycled waste

Units: kg/Year

waste mixed=USW generation-selective waste collection

Units: kg/Year

water total crop=(MAX(0,fodder desalinated water supply))+annual vol gav reuse

Total volumen of water requiered by active gavias. Units: m3/Year

WCO2E=2200

Waste CO2 Emission factor (Source: Castellani and Sala 2013). Units: g CO2/kg

Wind power

Data. Units: kwh/Year

ANNEX II

List of the extreme condition tests

1. *Drop of the tourist arrivals leads to a reduction of employment.*

TEXT DESCRIPTION: Unexpected drop of the tourist arrivals along five years (“etp dec”) would lead to a reduction of employment (“touristempl”).

VENSIM SYNTAXIS:

TEST INPUT: “etp dec”: etp=RC RAMP (etp, 0.5, 5, 1998)

CONSTRAIT: CONDITION: “etp dec”: IMPLIES: “touristempl”<=RC RAMP CHECK (0, “touristempl”, 0.5, 7, 1998)

TESTS RESULTS: **Figure A.1**

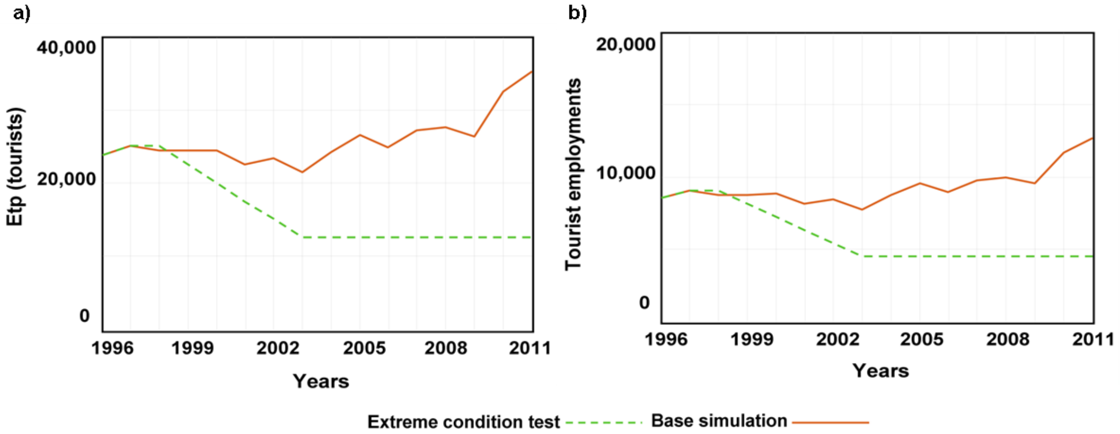

Figure A.1. Simulation of the extreme condition test: "*Drop of the tourist arrivals leads to a reduction of employment*". a) Input conditions; b) Expected effects.

2. *Extreme droughts lead to overgrazing.*

TEXT DESCRIPTION:

If the annual average rainfall was kept below or equal 40 mm, the overgrazing indicator would reach values over 1 after some years.

VENSIM SYNTAXIS:

TEST INPUT: rainfall<=40 mm

CONSTRAIT: CONDITION “rainfall<=40 mm”: IMPLIES: “overgrazing indicator<1”

TESTS RESULTS: **Figure A.2**

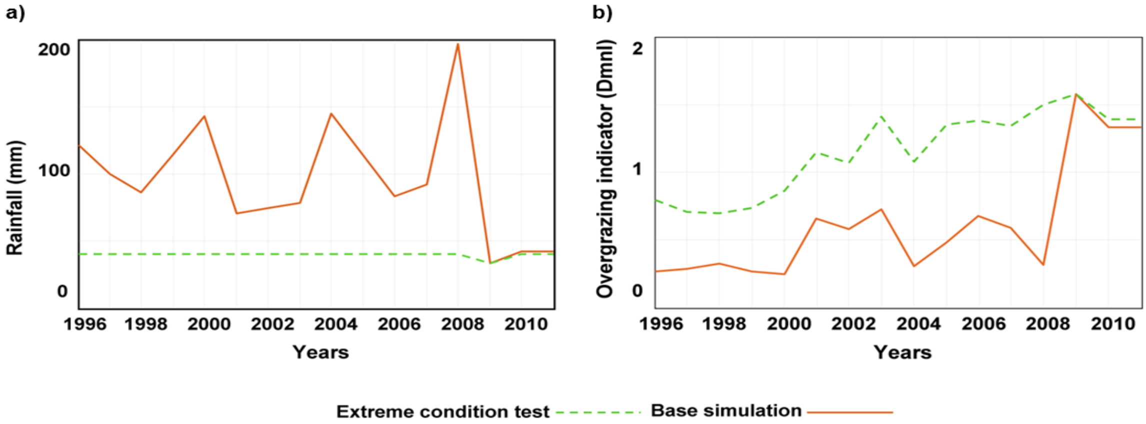

Figure A.2. Simulation of the extreme condition test: "*Extreme droughts lead to overgrazing*". a) Input conditions; b) Expected effects.

3. *An accelerated demand of built-up land leads to a reduction on houbara habitat*

TEXT DESCRIPTION:

If built up urban demand would boost for three years, a loss of houbara habitat would be expected.

VENSIM SYNTAXIS:

TEST INPUT: “TI built urban dem increases”: built urban=RC RAMP (built urban dem, 6, 3, 1998)

CONSTRAIT: CONDITION “TI built urban dem increases”: IMPLIES: habitat total hubara<=RC RAMP CHECK (3, habitat total hubara, 0.8, 5, 1998)

TESTS RESULTS: **Figure A.3**

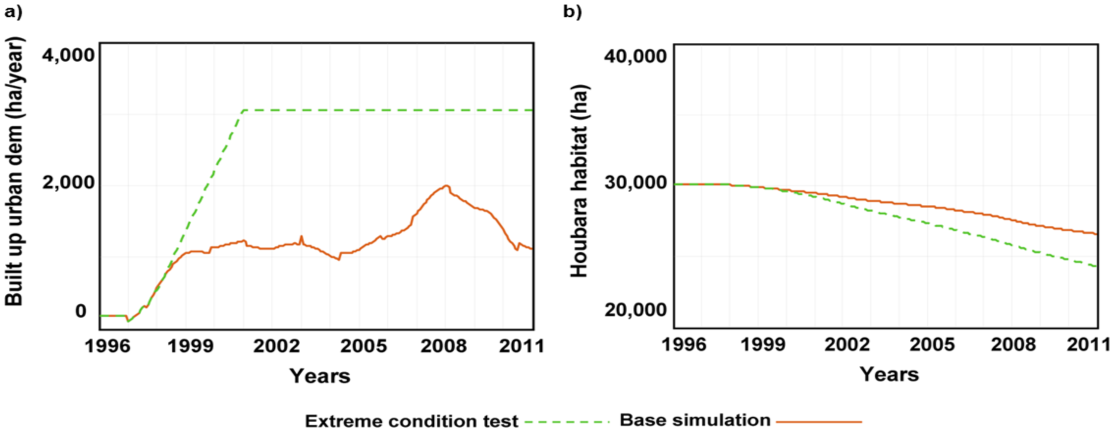

Figure A.3. Simulation of the extreme condition test: "*An accelerated demand of built-up land leads to a reduction on houbara habitat* ". a) Input conditions; b) Expected effects.

4. *An unexpected increase on the number of goats and sheeps would trigger overgrazing.*

TEXT DESCRIPTION: Unexpected increase on grazing cattle (“CGcpast“) along 4 years (“TI cgpastac inc”) would lead to overcome the overgrazing indicator (values>1).

VENSIM SYNTAXIS:

TEST INPUT: “TIcgpastac inc”: CGcpast=RC RAMP (CGcpast, 5, 7, 1997)

CONSTRAIT: CONDITION: “TI cgpastac inc CGcpast”: IMPLIES: overgrazing indicator>1

TESTS RESULTS: **Figure A.4**

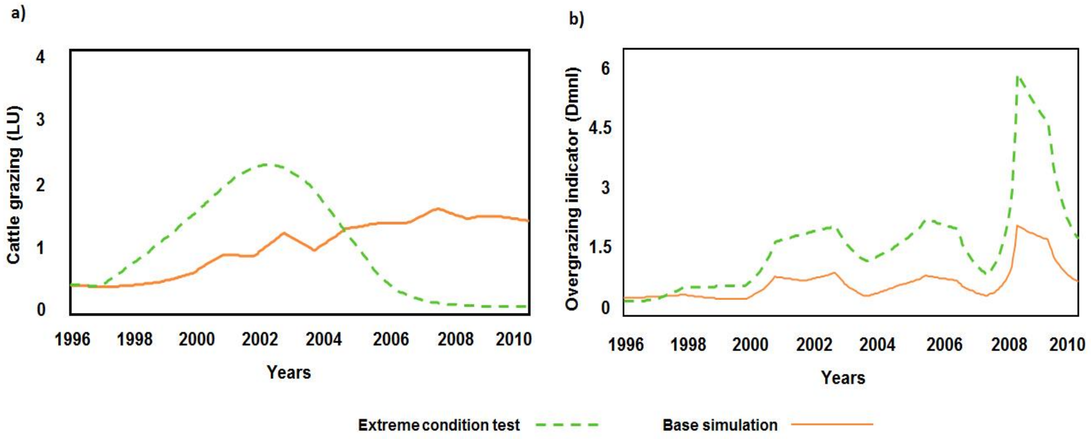

Figure A.4. Simulation of the extreme condition test: *"An unexpected increase on the number of goats and sheeps would trigger overgrazing*". a) Input conditions; b) Expected effects.

5. *A reduction on the GDPr would lead to a decrease on the equivalent tourist population*

TEXT DESCRIPTION: A negative GDP evolution of the most important markets for outbound tourism for the island (“GDP factor“) would reduce the equivalent tourist population (etp)

VENSIM SYNTAXIS:

TEST INPUT: “TI gdp effect reduce GDP factor”: GDP factor <=RC RAMP (GDP factor, 0.5, 2, 1998)

CONSTRAIT: CONDITION: “TI gdp effect reduce GDP factor”: IMPLIES: etp<=RC RAMP CHECK (1, etp, 0.3, 2, 1998)

TESTS RESULTS: **Figure A.5**

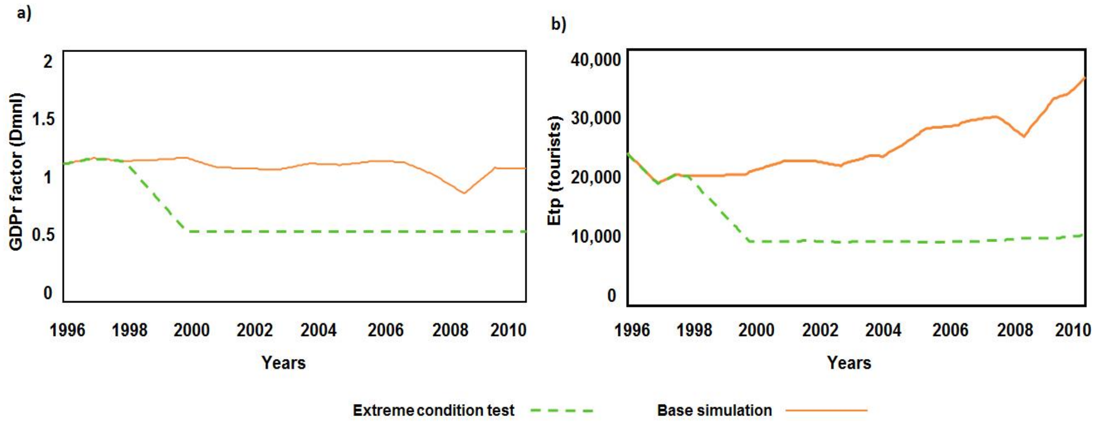

Figure A.5. Simulation of the extreme condition test: *"A reduction on the GDPr would decrease the equivalent tourist population*". a) Input conditions; b) Expected effects.

6. *If the occupancy rate decreases, the construction of new tourist accommodation would be stopped.*

TEXT DESCRIPTION: If the occupancy rate of the tourist accommodation decreases (“TI or decrease”), no increase of the tourist accommodation facilities (accomm fac) is expected.

VENSIM SYNTAXIS:

TEST INPUT: “TI or decrease”: occup rate=RC RAMP (occup rate, 0.6, 2, 1998)

CONSTRAIT: CONDITION: “TI or decrease”: IMPLIES: accomm fac<=RC RAMP CHECK (2, accomm fac, 0.7, 4, 1998)

TESTS RESULTS: **Figure A.6**

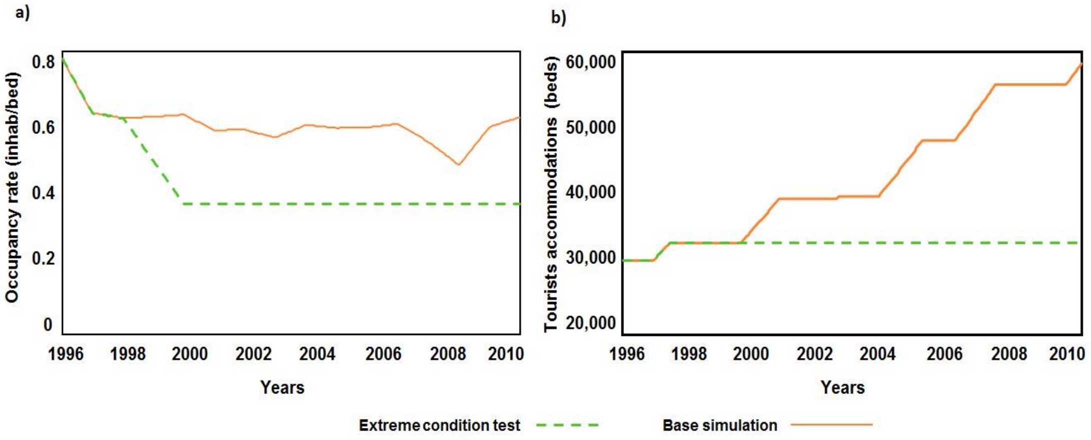

Figure A.6. Simulation of the extreme condition test: *"If the occupancy rate decreases, the construction of new tourist accommodation would be stopped*". a) Input conditions; b) Expected effects.

7. If the urban water demand increases, the consumption of electric energy rises

TEXT DESCRIPTION: If the urban water demand increases (“urb water dem”), the consumption of electric energy (elec E consump) would rise.

VENSIM SYNTAXIS:

TEST INPUT: “TI urb water dem inc”: urban desal demand>=RC RAMP (urban desal demand, 5, 3, 1997)

CONSTRAIT: CONDITION: “TI urb water dem inc”: IMPLIES: elec E consump >=RC RAMP CHECK (1, elec E consump, 1.1, 3, 1998)

TESTS RESULTS: **Figure A.7**

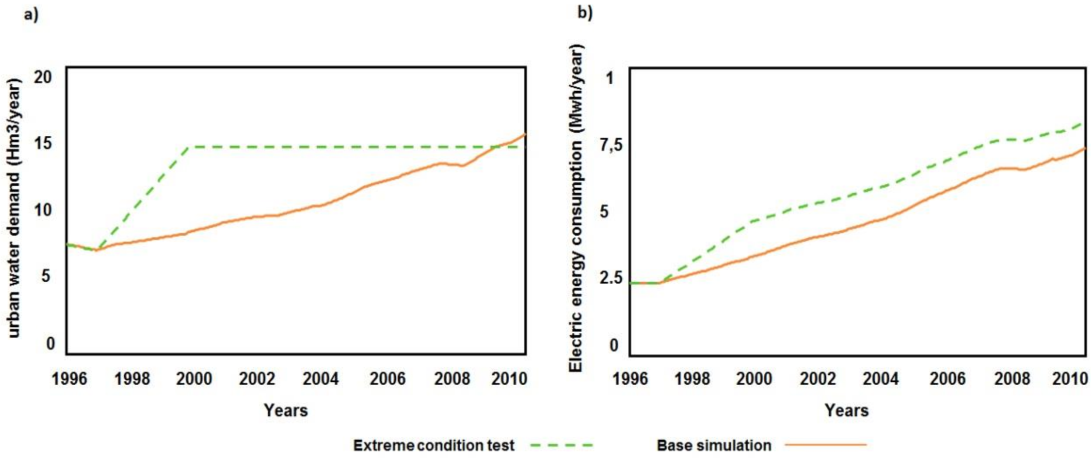

Figure A.7. Simulation of the extreme condition test: *"If the urban water demand increases, the consumption of electric energy rises*". a) Input conditions; b) Expected effects.

8. A reduction of the grazing cattle leads a reduction on the Egyptian vulture population

TEXT DESCRIPTION: A reduction of the grazing cattle (“CGcpast“) would lead a reduction on the Egyptian vulture population

VENSIM SYNTAXIS:

TEST INPUT: “TIcgpastac dec”: CGcpast= RC RAMP (CGcpast, 0.25, 2, 1997)

CONSTRAIT: CONDITION: “TIcgpastac dec”: IMPLIES: Egyptian vultures<=RC RAMP CHECK (1, Egyptian vultures, 0.9, 2, 1998)

TESTS RESULTS: **Figure A.8**

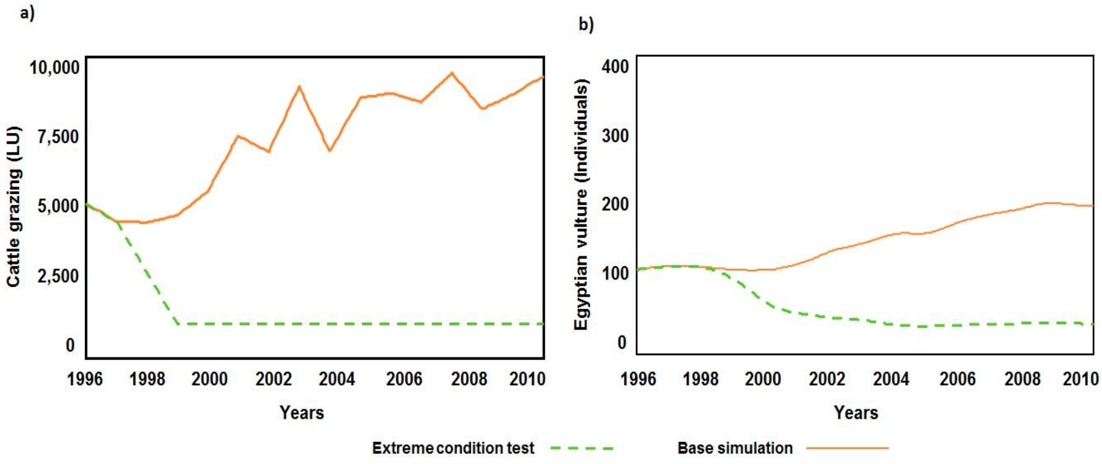

Figure A.8. Simulation of the extreme condition test: “*A reduction of the grazing cattle leads a reduction on the Egyptian vulture population*". a) Input conditions; b) Expected effects.

9. *An increase of the abandoned gavias would increase the secondary houbara habitat*

TEXT DESCRIPTION: The abandonment of gavias (“TI aband gav inc”) would increase the secondary houbara habitat

VENSIM SYNTAXIS:

TEST INPUT: “TI aband gav”: abandonment>=RC RAMP (abandonment, 5, 5, 1998)

CONSTRAIT: CONDITION: “TI aband gav”: IMPLIES: secondary habitat >=RC RAMP CHECK (1, secondary habitat, 1.1, 2, 1998)

TESTS RESULTS: **Figure A.9**

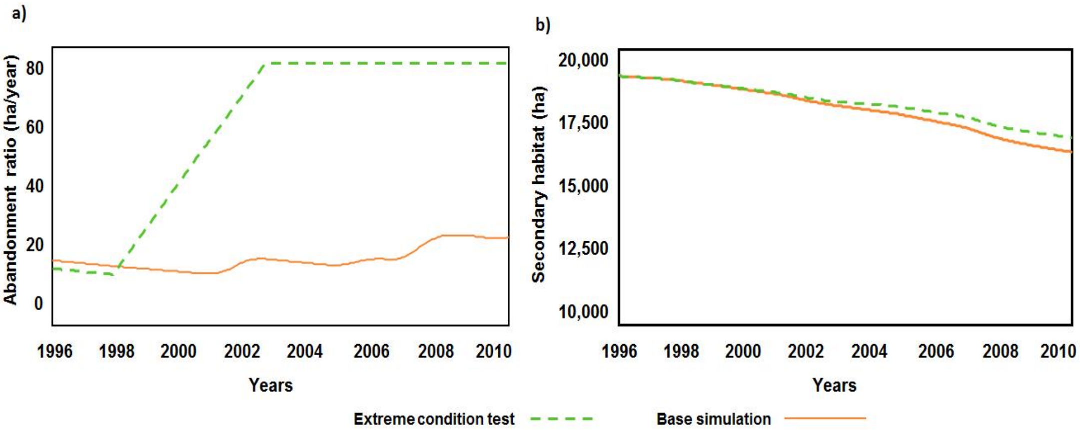

Figure A.9. Simulation of the extreme condition test: “*An increase of the abandoned gavias would increase the secondary houbara habitat*". a) Input conditions; b) Expected effects.

10. *An increase on new roads would negatively affect the houbara habitat*

TEXT DESCRIPTION: The construction of new roads (“TI roads inc”) would reduce the houbara habitat

VENSIM SYNTAXIS:

TEST INPUT: “TI roads inc”: new roads>=RC RAMP (new roads, 5, 2, 1998)

CONSTRAIT: CONDITION: “TI roads inc”: IMPLIES: houbara habitat<=RC RAMP CHECK (1, houbara habitat, 0.8, 2, 1998)

TESTS RESULTS: **Figure A.10**

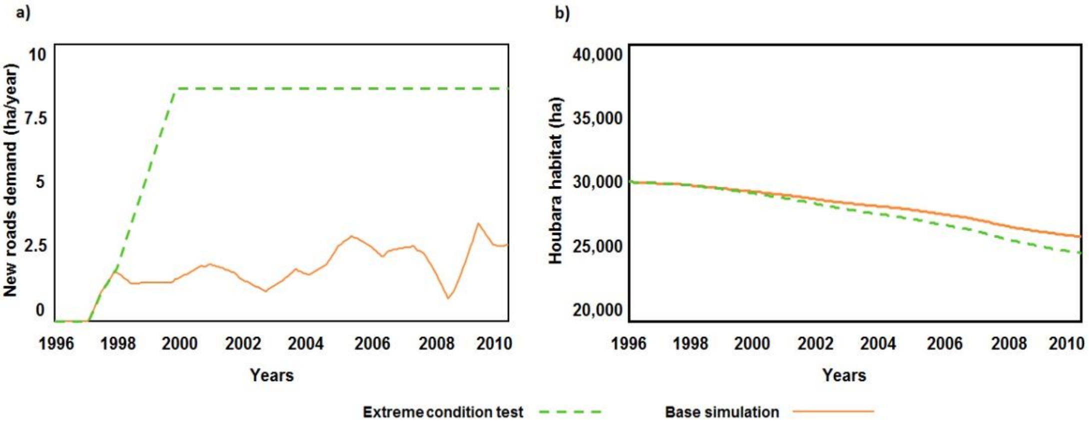

Figure A.10. Simulation of the extreme condition test: “*An increase on new roads would negatively affect the houbara habitat*". a) Input conditions; b) Expected effects.

11. An increase on active gavias would increase the groundwater recharge

TEXT DESCRIPTION: The increase on active gavias thanks to a restoration of abandoned gavias programme ("TI gav inc") would increase the groundwater recharge (gw recharge).

VENSIM SYNTAXIS:

TEST INPUT: "TI gav inc": gavias>=RC RAMP (gavias, 5, 3, 2000)

CONSTRAIT: CONDITION: "TI gav inc": IMPLIES: gw recharge >=RC RAMP CHECK (1, gw recharge, 1.1, 3, 2001)

TESTS RESULTS: **Figure A.11**

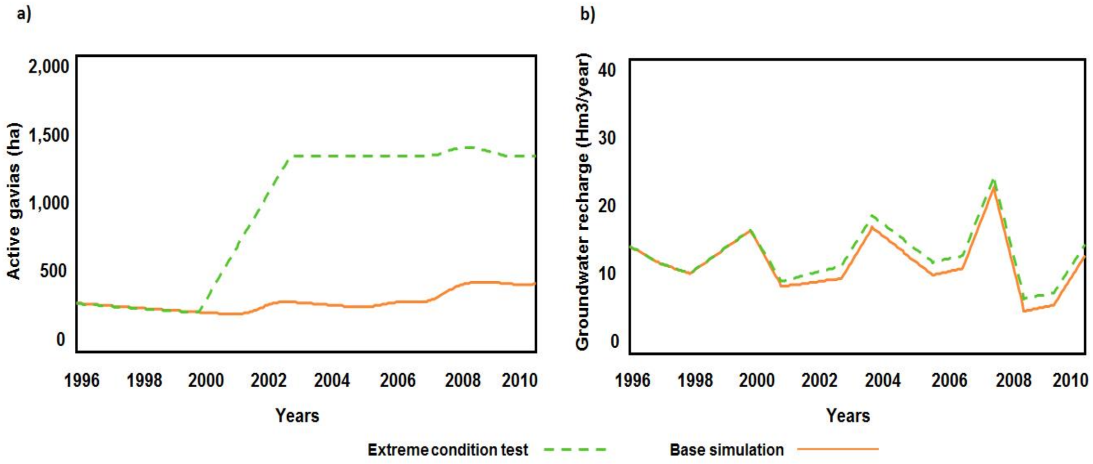

Figure A.11. Simulation of the extreme condition test: "*An increase on active gavias would increase the* groundwater *recharge*". a) Input conditions; b) Expected effects.

12. A reduction of the flights would decrease the CO2 pc

TEXT DESCRIPTION: The reduction of the number of visitors who arrive by plane to Fuerteventura airport ("TI visitors dec") would rise down the per capita CO_2 emissions (CO_2 pc)

VENSIM SYNTAXIS:

TEST INPUT: "TI visitors dec": visitors=RC RAMP (visitors, 0.5, 3, 1998)

CONSTRAIT: CONDITION: "TI visitors dec": IMPLIES: CO_2 pc<=RC RAMP CHECK (1, CO_2 pc, 0.8, 3, 1998)

TESTS RESULTS: **Figure A.12**

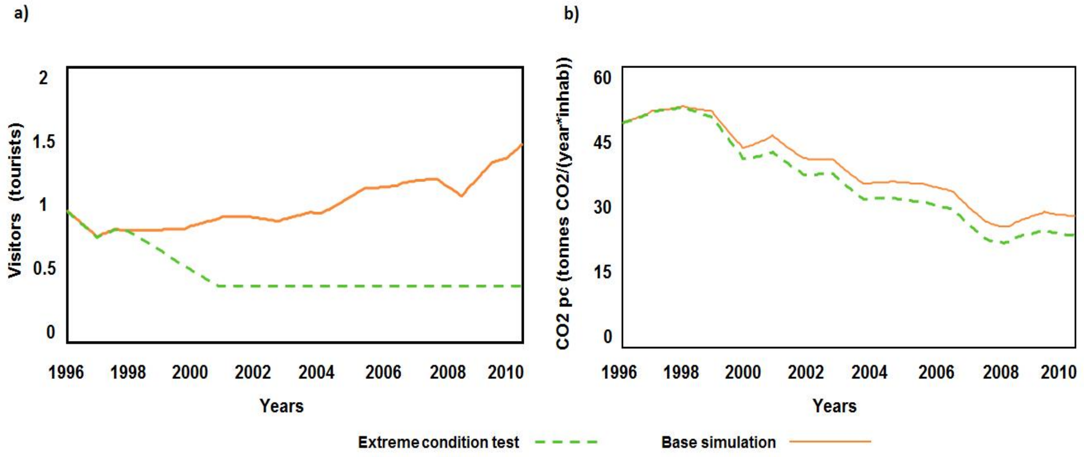

Figure A.12. Simulation of the extreme condition test: "*A reduction of the flights would decrease the CO_2 pc*". a) Input conditions; b) Expected effects.

13. A reduction of the GDPca decreases the electric energy demand

TEXT DESCRIPTION: The reduction of the number of the GDPca (“TI GDPca”) would rise down the electric energy demand of the resident population (demand E respop)

VENSIM SYNTAXIS:

TEST INPUT: “TI GDPca”: GDPca=RC RAMP (GDPca, 0.1, 2, 1998)

CONSTRAIT: CONDITION: “TI GDPca”: IMPLIES: demand E respop<=RC RAMP CHECK (1, demand E respop, 0.9, 3, 1998)

TESTS RESULTS: **Figure A.13**

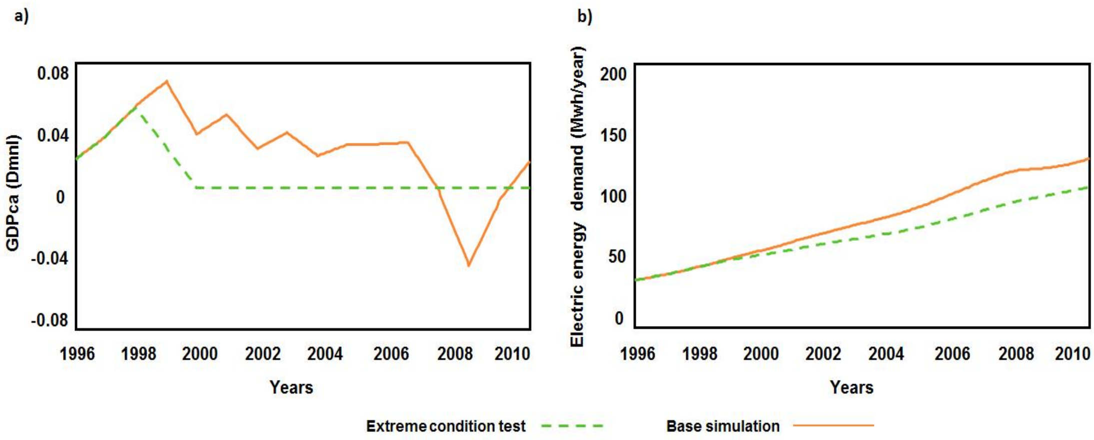

Figure A.13. Simulation of the extreme condition test: “*A reduction of the GDPca decreases the electric energy demand*". a) Input conditions; b) Expected effects.

14. A boost of renewable energy triggers an increase of the SER indicator

TEXT DESCRIPTION: An increase of the renewable energy (“TI renew E inc”) would rise up the share of renewable energy indicator (SER)

VENSIM SYNTAXIS:

TEST INPUT: “TI renew E inc”: renewable energy >=RC RAMP (renewable energy, 2.5, 3, 1998)

CONSTRAIT: CONDITION: “TI renew E inc”: IMPLIES: SER<=RC RAMP CHECK (1, SER, 1.5, 3, 1999)

TESTS RESULTS: **Figure A.14**

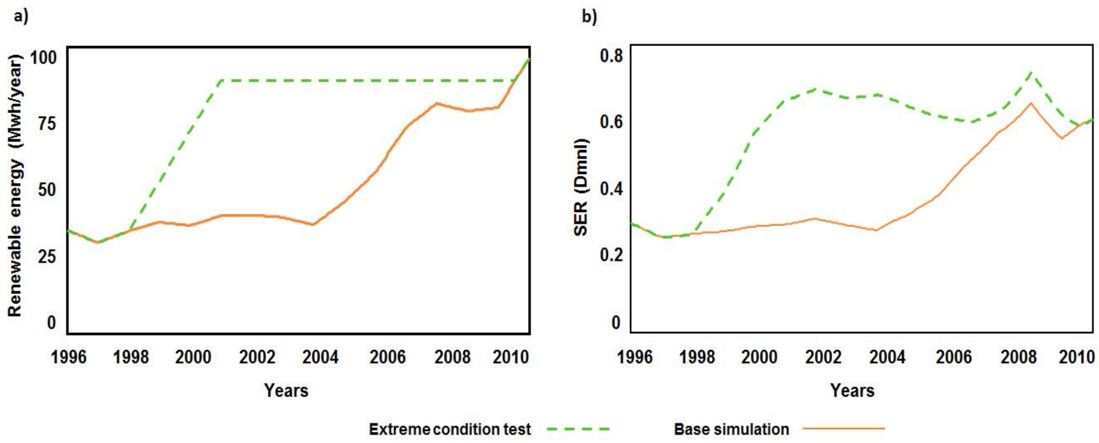

Figure A.14. Simulation of the extreme condition test: “*A boost of renewable energy triggers an increase of the SER indicator*". a) Input conditions; b) Expected effects.

15. A reduction of grazing increases the fodder importation needs

TEXT DESCRIPTION: A reduction of the grazing cattle (“CGcpast“) would lead an increase on the fodder importation needs (fin)

VENSIM SYNTAXIS:

TEST INPUT: “TIcgpastac dec”: CGcpast= RC RAMP (CGcpast, 0.25, 2, 1997)

CONSTRAIT: CONDITION: “TIcgpastac dec”: IMPLIES: fin>=RC RAMP CHECK (1, fin, 1.2, 3, 1999)

TESTS RESULTS: **Figure A.15**

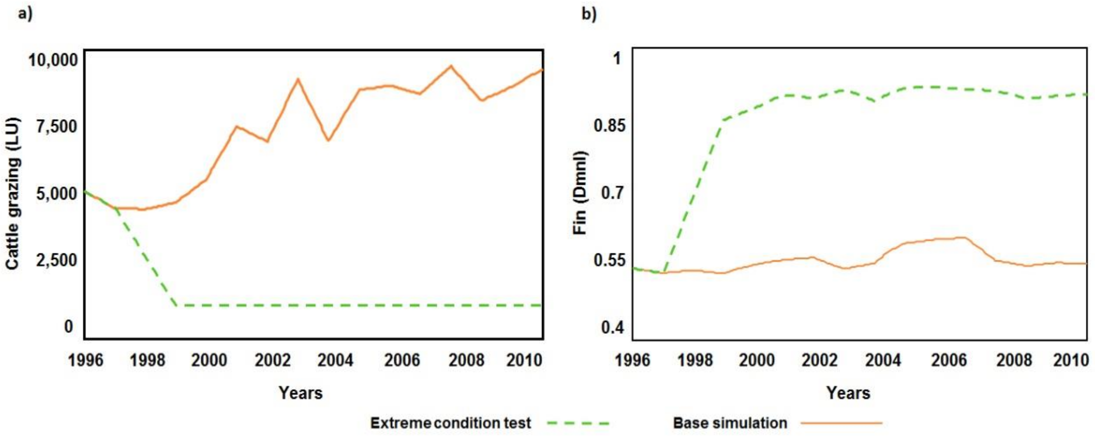

Figure A.15. Simulation of the extreme condition test: “*A reduction of grazing increases the fodder importation needs*". a) Input conditions; b) Expected effects.

16. An increase on resident population negatively affects the houbara habitat

TEXT DESCRIPTION: If the resident population boosted along 5 consecutive years (“TI respop inc”), the houbara habitat would be negatively affected.

VENSIM SYNTAXIS:

TEST INPUT: “TI respop inc”: resident population=RC RAMP (resident population, 2, 5, 1998)

CONSTRAIT: CONDITION: “TI respop inc”: IMPLIES: habitat houbara<=RC RAMP CHECK (1, habitat houbara, 0.8, 3, 1999)

TESTS RESULTS: **Figure A.16**

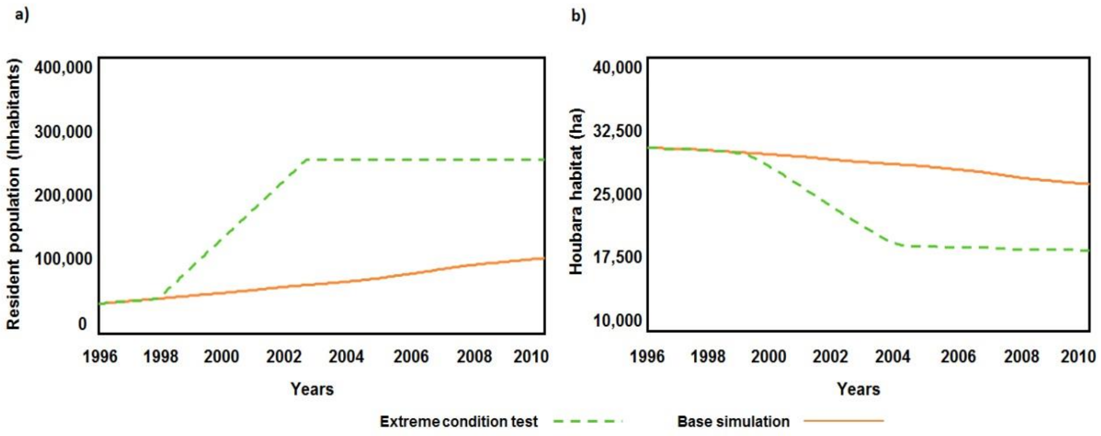

Figure A.16. Simulation of the extreme condition test: “*An increase on resident population negatively affects the houbara habitat*". a) Input conditions; b) Expected effects.

17. An increase on resident population would increase no natural deaths of Egyptian vultures

TEXT DESCRIPTION: If the resident population triples in 5 years (“TI respop tri”), no natural mortality of Egyptian vultures increases.

VENSIM SYNTAXIS:

TEST INPUT: “TI respop inc”: resident population=RC RAMP (resident population, 2, 5, 1998)

CONSTRAIT: CONDITION: “TI respop tri”: IMPLIES: mort no natural>=RC RAMP CHECK (1, mort no natural, 1.1, 3, 1999)

TESTS RESULTS: **Figure A.17**

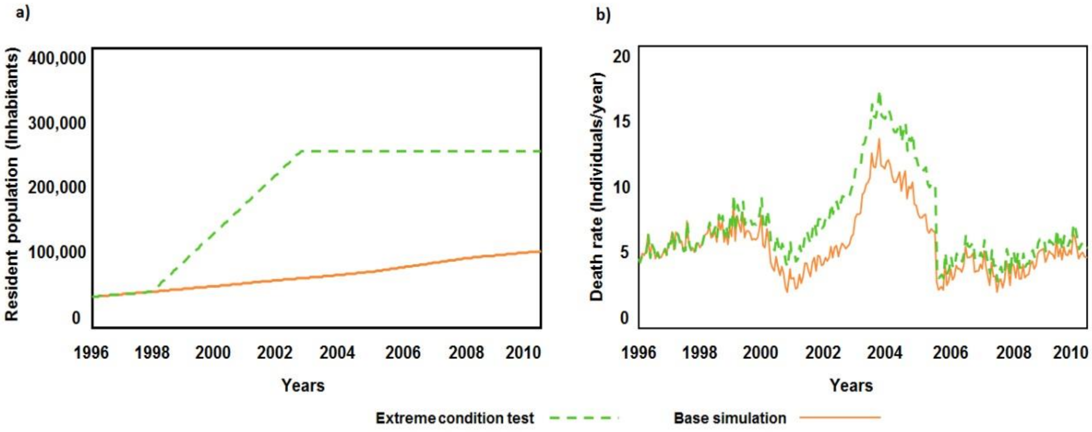

Figure A.17. Simulation of the extreme condition test: “*An increase on resident population would increase no natural deaths of Egyptian vultures*". a) Input conditions; b) Expected effects.

18. An increase on poisoning increases no natural deaths of Egyptian vultures

TEXT DESCRIPTION: An increase on poisoning (“TI poison inc”) would cause a decrease on Egyptian vultures population

VENSIM SYNTAXIS:

TEST INPUT: “TI poison inc”: posoning>=RC RAMP (posioning, 3, 2, 1998)

CONSTRAIT: CONDITION: “TI poison inc”: IMPLIES: Egyptian vultures <=RC RAMP CHECK (1, Egyptian vultures, 0.9, 2, 1998)

TESTS RESULTS: **Figure A.18**

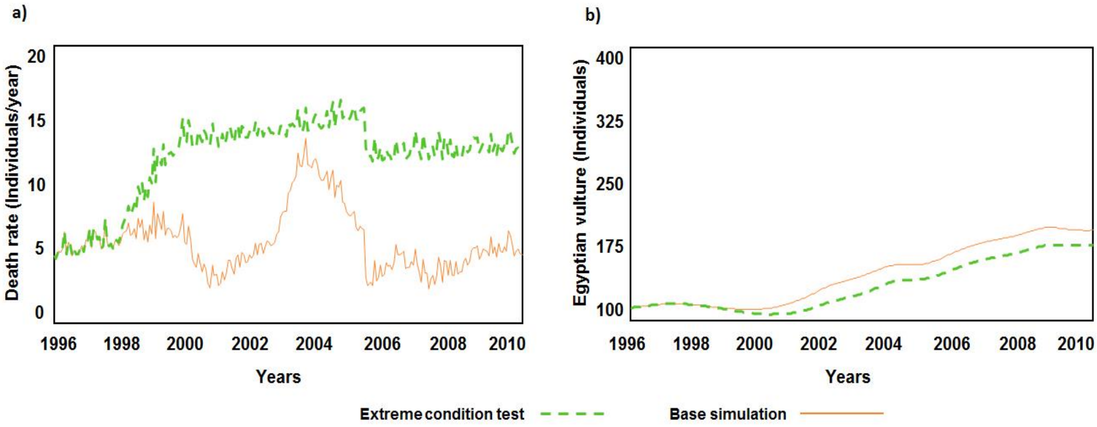

Figure A.18. Simulation of the extreme condition test: “*An increase on poisoning increases no natural deaths of Egyptian vultures*". a) Input conditions; b) Expected effects.

19. An increase on electric energy consumption would rise up the CO2pc

TEXT DESCRIPTION: An increase on *electric energy consumption* (“TI elec E consum inc”) would rise up the per capita CO_2 emissions (CO_2 pc)

VENSIM SYNTAXIS:

TEST INPUT: “TI elec E consum inc”: elec E consum =RC RAMP (elec E consum, 5, 3, 1997)

CONSTRAIT: CONDITION: “TI elec E consum inc”: IMPLIES: CO_2 pc>=RC RAMP CHECK (1, CO_2 pc, 1.1, 3, 2001)

TESTS RESULTS: **Figure A.19**

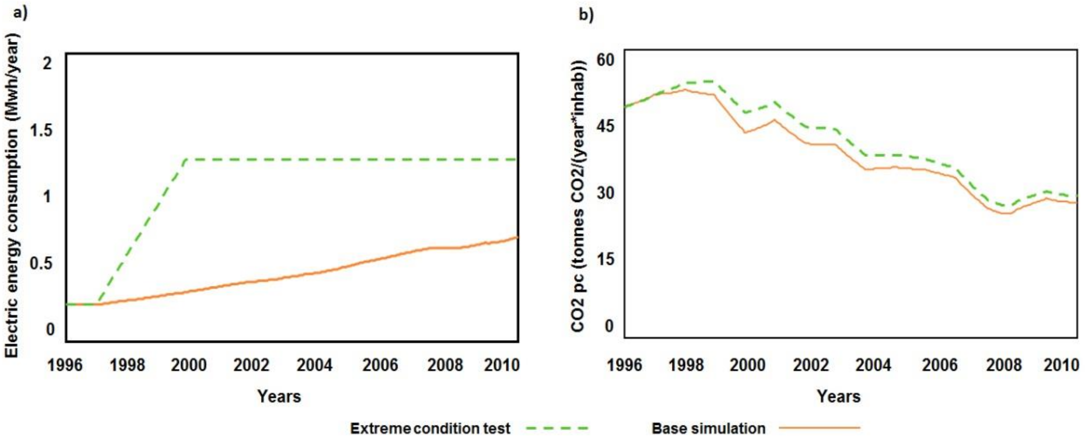

Figure A.19. Simulation of the extreme condition test: “*An increase on electric energy consumption would rise up the CO_2pc*". a) Input conditions; b) Expected effects.

20. A decrease on total population would reduce the USW generation

TEXT DESCRIPTION: A decrease on *total population* (“TI totpop dec”) would reduce the generation of urban solid waste (USW generation)

VENSIM SYNTAXIS:

TEST INPUT: “TI totpop dec”: tot population<=RC RAMP (tot population, 0.1, 3, 1997)

CONSTRAIT: CONDITION: “TI totpop dec”: IMPLIES: USW generation<=RC RAMP CHECK (1, USW generation, 0.5, 3, 1998)

TESTS RESULTS: **Figure A.20**

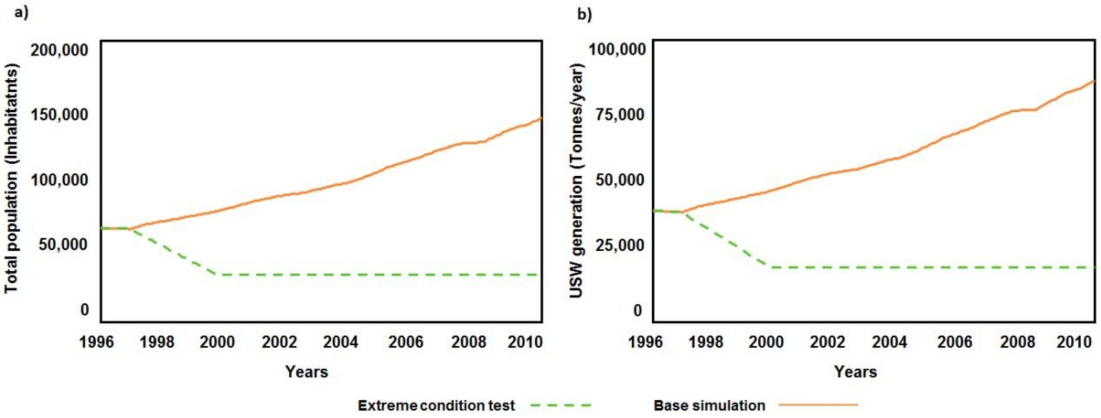

Figure A.20. Simulation of the extreme condition test: “*A decrease on total population would reduce the USW generation*". a) Input conditions; b) Expected effects.

21. The reduction of USW generation per capita ratio would reduce the indirect emissions of CO_2

TEXT DESCRIPTION: A decrease on of USW generation per capita ratio (“TI TGEREURBpc red”) would reduce the indirect emissions of CO_2 from waste.

VENSIM SYNTAXIS:

TEST INPUT: “TI TGEREURBpc red”: TGEREURBpc <= TGEREURBpc*0.5

CONSTRAIT: CONDITION: “TI TGEREURBpc red”: IMPLIES: Indirect emission of generated waste<=RC RAMP CHECK (1, Indirect emission of generated waste, 0.75, 3, 1998)

TESTS RESULTS: **Figure A.21**

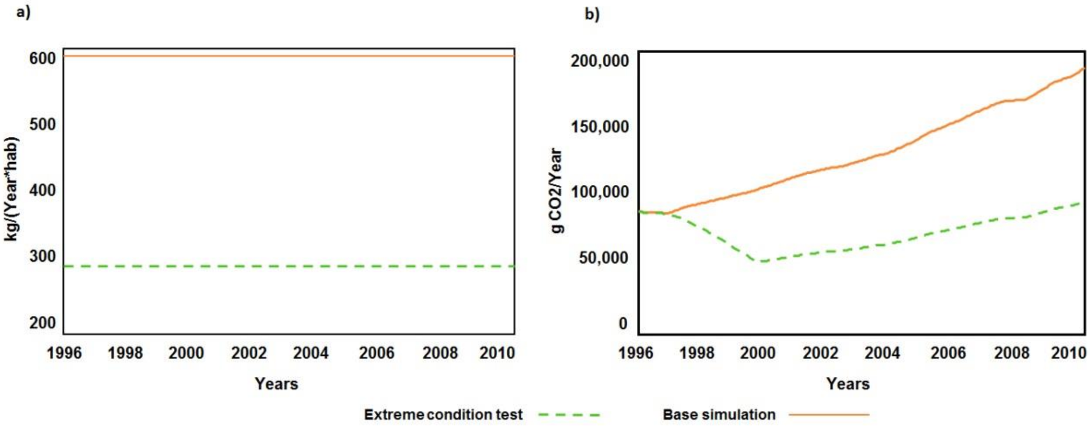

Figure A.21. Simulation of the extreme condition test: “*The reduction of USW generation per capita ratio would reduce the indirect emissions of CO_2*". a) Input conditions; b) Expected effects.

22. An extreme drought would boost the groundwater demand for irrigation

TEXT DESCRIPTION: An extreme drought (“TI drought”) would boost the groundwater demand for irrigation

VENSIM SYNTAXIS:

TEST INPUT: “TI drought”: pre act<=10

CONSTRAIT: CONDITION: “TI drought”: IMPLIES: gwp irrig<=RC RAMP CHECK (1, gwp irrig, 1.25, 3, 1997)

TESTS RESULTS: **Figure A.22**

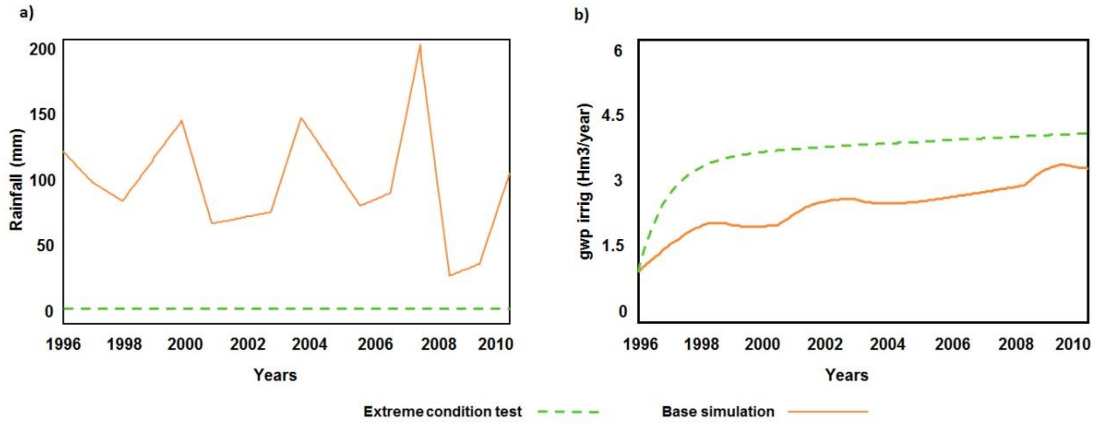

Figure A.22. Simulation of the extreme condition test: “*An extreme drought would boost the groundwater demand for irrigation*". a) Input conditions; b) Expected effects.

23. An increase on the treatment water proportion from resident population would give raise the indicator treated sewage proportion.

TEXT DESCRIPTION: A reduction of the treatment water proportion from resident population ("TI RPTREATMENTP red") would reduce the indicator treated sewage proportion (treat-sewage prop).

VENSIM SYNTAXIS:

TEST INPUT: "TI RPTREATMENTP red": RPTREATMENTP>= RPTREATMENTP*2

CONSTRAIT: CONDITION: "TI drought": IMPLIES: treat-sewage prop>=RC RAMP CHECK (1, treat-sewage prop, 1.5, 3, 1998)

TESTS RESULTS: **Figure A.23**

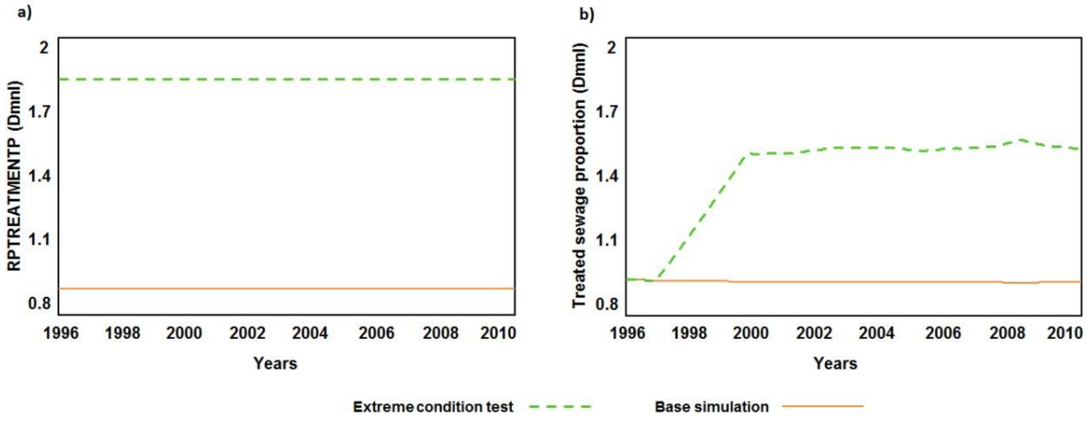

Figure A.23. Simulation of the extreme condition test: "*A reduction of the treatment water proportion from resident population would reduce the indicator treated sewage proportion*". a) Input conditions; b) Expected effects.

24. An increase of the resident population would give raise the artificial land proportion

TEXT DESCRIPTION: An increase of the resident population ("TI respop inc") would give raise the artificial land proportion (alp).

VENSIM SYNTAXIS:

TEST INPUT: "TI respop inc": resident population>=RC RAMP (resident population, 5, 5, 1998)

CONSTRAIT: CONDITION: "TI respop inc": IMPLIES: alp>=RC RAMP CHECK (1, alp, 1.2, 2, 1999)

TESTS RESULTS: **Figure A.24**

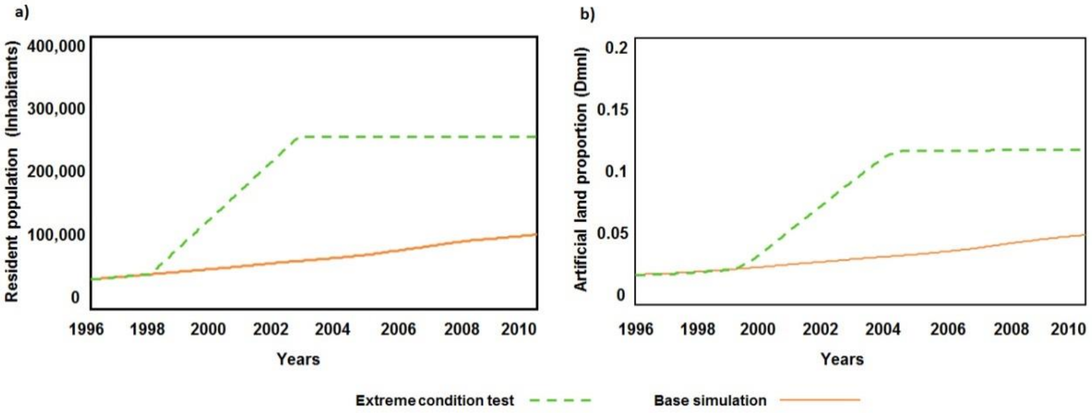

Figure A.24. Simulation of the extreme condition test: "*An increase of the resident population would give raise the artificial land proportion*". a) Input conditions; b) Expected effects.

25. *An increase on the number of tourist accommodation would reduce the natural vegetation*

TEXT DESCRIPTION: An increase on the number of tourist accommodation (“TI accomm inc”) would reduce the natural vegetation (natural veg)

VENSIM SYNTAXIS:

TEST INPUT: “TI accomm inc”: tourist accommodation>=RC RAMP (tourist accommodation, 2.5, 3, 1998)

CONSTRAIT: CONDITION: “TI accomm inc”: IMPLIES: natural veg>=RC RAMP CHECK (1, natural veg, 0.9, 3, 1999)

TESTS RESULTS: **Figure A.25**

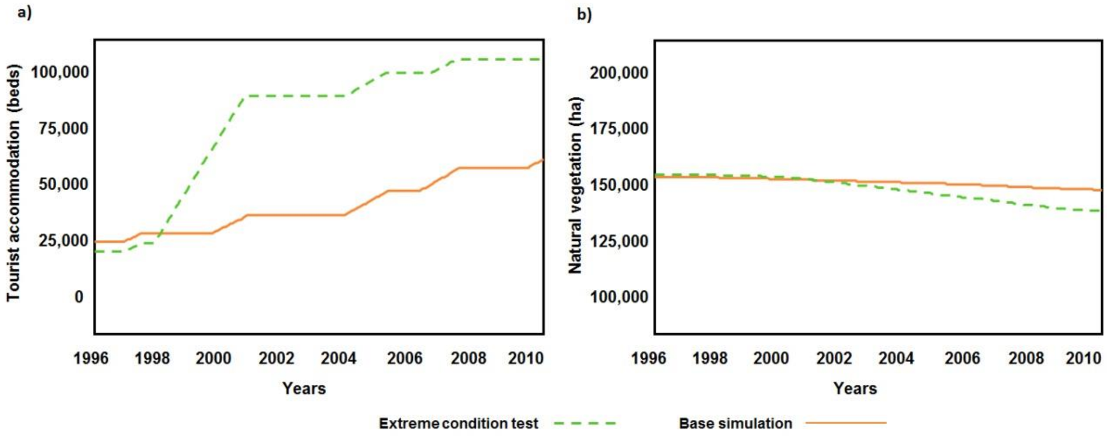

Figure A.25. Simulation of the extreme condition test: “*An increase on the number of tourist accommodation would reduce the natural vegetation*”. a) Input conditions; b) Expected effects.

ANNEX III

One factor at a time (OAT)

	TARGET VARIABLES																	
PARAMETERS	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**	**V11**	**V12**	**V13**	**V14**	**V15**	**V16**	**V17**	**V18**
ABROAD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	43.0	0.0	0.0	0.0	0.0	0.0	0.0
ABROAD (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42.7	0.0	0.0	0.0	0.0	0.0	0.0
AIR	62.8	0.0	0.0	0.0	0.0	57.7	21.1	26.8	0.0	49.2	9.0	30.3	41.9	0.0	41.9	0.0	0.0	49.9
ARC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
AVERGOODS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.9	0.0	0.0	0.0	0.0	0.0	0.0
AVERGOODS (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.1	0.0	0.0	0.0	0.0	0.0	0.0
AVERSTAY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.3	0.0	0.0	0.0	0.0	0.0	0.0
AVERSTAY (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	48.8	0.0	0.0	0.0	0.0	0.0	0.0
B	88.8	28.0	0.0	0.0	0.0	80.8	88.6	36.8	2.5	49.4	32.3	0.0	27.7	0.0	27.9	11.1	48.1	51.6
BIR BASE	326.6	98.1	0.0	0.0	0.0	304.7	295.8	135.6	9.1	194.6	114.9	0.0	120.5	0.0	120.2	37.7	189.1	202.4
CFBUEU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO2FACTORgav	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
CO2FACTORgav (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
CO2FACTORgc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
CO2FACTORirrig	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
CPRE	0.0	314.1	0.0	106.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CPRE (RR)	0.0	359.8	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
desal CORRALEJO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
desal CORRALEJO (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DIST1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
DIST2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0
DIST3G	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.2	0.0	0.0	0.0	0.0	0.0	0.0
DIST3UK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0	0.0	0.0	0.0
DIST4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
DVEF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.8	0.0	0.0	0.0	0.0	0.0	0.0
ECO2E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.8	0.0	0.0	0.0	0.0	0.0	0.0
ECO2E (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.7	0.0	0.0	0.0	0.0	0.0	0.0
EECBR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	48.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EICF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.4	0.0	0.0	0.0	0.0	0.0	0.0

PARAMETERS	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18
elGCC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	92.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EVAPORATION	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EVAPORATION (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EVTp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.6	0.0	0.0	0.0	0.0
FCO2E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.4	0.0	0.0	0.0	0.0	0.0	0.0
FCO2E (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.1	0.0	0.0	0.0	0.0	0.0	0.0
FLOWSEAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FLOWSPRING	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FODDER YIELD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FODDER YIELD (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FUEL CONSs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.1	0.0	0.0	0.0	0.0	0.0	0.0
FUEL CONSs (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.0	0.0	0.0	0.0	0.0	0.0	0.0
GCR	0.0	0.0	113.4	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GDPcaFACTOR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0
GDPcaFACTOR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0
GOLFCONR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	53.0	0.0	0.0	0.0	0.0
GOLFCONR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	53.0	0.0	0.0	0.0	0.0
GOLFLOSR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0
GOLFLOSR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.7	0.0	0.0	0.0	0.0
GVEF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
HCRpermabandon	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HCRac	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HCRtracks	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HCRroads	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HCRub	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HOTEL ACCOMMODAT LAND DEM	1.9	0.5	0.2	0.0	0.0	0.4	0.4	0.4	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HOTEL ACCOMMODAT LAND DEM (RR)	1.8	0.5	0.2	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ICR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	93.4	0.0	0.0	0.0	0.0	0.0

PARAMETERS	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18
IR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	93.9	0.0	0.0	0.0	0.0	0.0
IR gavias	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0	0.0
IR gavias (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.0	0.0
IRCONR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.5	43.6	0.0	0.0	0.0	0.0
IRCONR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.4	43.4	0.0	0.0	0.0	0.0
IRLOSR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.0	0.0	0.0	0.0	0.0
IRLOSR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.0	0.0	0.0	0.0	0.0
ISLAND	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0
ISLAND (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Kc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.60	0.0	0.0	0.0	0.0	0.0
Kc (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kn	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LOSS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	4.6	23.5	23.5	0.0	0.0
LOSS (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	4.9	23.6	23.4	0.0	0.0
MAX ACCOMMODATION	48.3	0.0	0.0	0.0	0.0	47.1	26.8	20.7	3.2	43.1	47.4	0.0	0.0	0.0	39.8	39.7	0.0	43.5
MAX ACCOMMODATION (RR)	20.6	0.0	0.0	0.0	0.0	19.5	7.8	5.1	1.3	12.4	22.4	0.0	0.0	0.0	17.5	17.4	0.0	21.2
MF GDPca INMIG	64.7	18.7	0.0	0.0	0.0	60.0	49.7	27.3	5.7	39.6	0.0	11.7	0.0	0.0	24.1	0.0	0.0	0.0
MFACTOR GDP	11.3	0.0	0.0	0.0	0.0	9.0	11.7	4.7	0.0	5.9	0.0	3.2	0.0	0.0	3.3	0.0	0.0	0.0
MFACTOR IET	214.7	55.9	0.0	0.0	0.0	232.7	150.6	91.9	6.3	217.5	1012.1	178.5	0.0	0.0	207.1	206.9	13.5	130.2
MIR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MOR	2.9	0.6	0.0	0.0	0.0	2.9	2.1	1.2	0.1	1.8	0.9	0.0	0.3	0.0	0.8	0.0	0.0	1.2
MOR (RR)	2.9	0.0	0.0	0.0	0.0	2.9	1.5	1.2	0.3	2.0	0.8	0.0	1.2	0.0	1.0	0.0	0.0	2.3
NBEACH THRESHOLD	17.1	0.0	0.0	0.0	0.0	22.8	42.8	7.7	0.0	26.4	29.8	29.7	29.8	0.0	29.7	0.0	0.0	26.2
NBEACH THRESHOLD (RR)	0.5	0.0	0.0	0.0	0.0	1.5	2.3	7.3	0.0	2.5	2.8	4.6	3.5	0.0	3.5	0.0	0.0	2.5
NEEfactor	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.2	0.0	0.0	0.0	0.0	0.0	0.0
NEEfactor (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.2	0.0	0.0	0.0	0.0	0.0	0.0
NGP	0.0	341.9	0.0	100.0	100.0	0.0	0.0	0.0	73.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NGP (RR)	0.0	297.9	0.0	100.0	117.4	0.0	0.0	0.0	73.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NONHOT ACCOM LAND DEM	0.9	0.2	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NONHOT ACCOM LAND DEM (RR)	0.9	0.2	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

PARAMETERS	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18
NONHOT ACCOM RATIO	0.5	0.2	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NONHOT ACCOM RATIO (RR)	0.5	0.2	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NOTOURIST EMPLOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PEGcpl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PEGspl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PENINSULA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0
PENINSULA (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0
PLRpc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PLRpc (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
preFACTOR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.5	0.0	0.0	0.0	0.0	0.0	0.0
preFACTOR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.5	0.0	0.0	0.0	0.0	0.0	0.0
ptotFACTOR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0
ratioG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.2	0.0	0.0	0.0	0.0	0.0	0.0
ratioG (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.9	0.0	0.0	0.0	0.0	0.0	0.0
ratioUK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.9	0.0	0.0	0.0	0.0	0.0	0.0
ratioUK (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.2	0.0	0.0	0.0	0.0	0.0	0.0
REUSR	0.0	0.0	53.2	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
REUSR (RR)	0.0	0.0	64.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ROADSn	0.0	0.1	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RPOPAQUIFER	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	19.6	8.9	8.9	0.0	0.0
RPOPAQUIFER (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	20.5	9.3	9.2	0.0	0.0
RPOPCONRbase	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.8	0.0	0.0	0.0	19.6	65.0	65.0	6.0	0.0
RPOPCONRbase (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.7	0.0	0.0	0.0	19.6	65.1	65.0	6.0	0.3
RPSEWAGEPROP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.2	0.0
RPTREATMENTP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	54.2	0.0
RPTREATMENTP (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	67.5	0.0
RT	0.0	86.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RT (RR)	0.0	163.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RUNOFFcte	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
RUNOFFcte (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0

PARAMETERS	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18
SCG	2.1	0.6	0.0	0.0	0.0	0.0	0.6	0.5	0.0	0.0	0.0	0.0	0.0	53.3	0.0	0.0	0.0	0.0
SCG (RR)	2.3	0.6	0.0	0.0	0.0	0.0	0.1	0.6	0.0	0.0	0.0	0.0	0.0	52.9	0.0	0.0	0.0	0.0
SCO2E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.5	0.0	0.0	0.0	0.0	0.0	0.0
SCO2E (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.5	0.0	0.0	0.0	0.0	0.0	0.0
SEADES CONVR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	194.0	0.0	0.0
SEADES CONVR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	148.9	0.0	0.0
SEADESCAP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SEWAGE PROP TUR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	0.0
SEWAGE PROP TUR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
SFACTOR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.1	0.0	0.0	0.0	0.0	0.0	0.0
SFACTOR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.1	0.0	0.0	0.0	0.0	0.0	0.0
shipCAPACITY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
ST	1.5	0.3	0.0	0.0	0.0	1.4	0.4	0.6	0.1	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ST (RR)	0.8	0.5	0.8	0.0	0.0	0.3	2.8	0.1	0.5	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TCNE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TCEO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	68.4	42.8	13.5	0.0	0.0	0.0	0.0	0.0	0.0
TCEO (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	68.2	41.1	12.0	0.0	0.0	0.0	0.0	0.0	0.0
TCEOne	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TCONBOV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TCONCAPROV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TCONCAPROV (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TCONPORC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TCONPORC (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TCV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42.4	59.5	0.0	0.0	35.2	0.0	0.0	0.0	0.0
TCV (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	41.9	50.5	0.0	0.0	30.4	0.0	0.0	0.0	0.0
TEMIG BASE	36.1	8.9	0.0	0.0	0.0	25.2	20.0	15.0	1.0	22.3	23.3	0.0	0.0	15.3	11.6	10.8	10.8	23.1
TEMIG BASE (RR)	39.4	10.8	0.0	0.0	0.0	38.3	31.0	16.5	3.4	25.2	26.0	0.0	0.0	13.7	14.4	14.3	14.3	26.4
TES	0.0	23.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TGEREURBpc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	108.6
TGEREURBpc (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	108.9
THRESHOLD RO	129.7	20.6	0.0	7.0	51.0	152.2	124.5	55.7	3.9	147.1	508.8	129.8	0.0	15.3	143.5	143.5	6.4	147.4

PARAMETERS	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18
THRESHOLD RO (RR)	398.4	48.8	0.0	9.2	61.5	431.1	361.2	170.5	10.9	418.2	926.6	371.8	0.0	13.7	409.5	409.1	11.7	419.1
TINGBOV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TINGCAPROV	0.0	0.0	0.0	0.0	101.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TINGCAPROV (RR)	0.0	0.0	0.0	0.0	102.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TINGPORC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TINMIGDPca	0.2	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TKWM3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.4	4.7	1.5	0.0	0.0	0.0	0.0	0.0	0.0
TKWM3 (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.5	4.6	1.5	0.0	0.0	0.0	0.0	0.0	0.0
TMONT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	41.8	59.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TPP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.4	83.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRACKSn	0.0	0.1	0.0	0.0	0.0	0.1	0.0	9.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRACKSn (RR)	0.0	0.1	0.0	0.0	0.0	0.1	0.0	9.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRECRES	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	62.1
TRECRES (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	99.5
TRECSELEC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.1
TRECSELEC (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.2
TSUCVOpc	62.0	13.3	0.0	0.0	0.0	13.0	7.6	13.5	0.0	11.9	1.3	1.1	0.0	0.3	3.6	3.1	0.0	0.0
TURCONR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	2.3	0.5	0.0	20.0	34.6	34.6	0.0	0.0
TURCONR (RR)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	2.4	0.5	0.0	19.9	34.5	34.5	0.0	0.0
WCO2E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0

V1: Built urban; V2: High quality vegetation proportion; V3: Gavias proportion; V4: Overgrazing index; V5: Fodder importation needs; V6: Resident population; V7: Equivalent tourist population; V8: Houbara habitat proportion; V9: Egyptian vultures proportion; V10: Electric energy consumption; V11: Share of renewable energy; V12: Per capita CO$_2$ emissions; V13: Groundwater recharge; V14: Groundwater pumping; V15: Desalinated water; V16: Brine production; V17: Treated sewage proportion; V18: Recycled waste; RR: Reasonable range

ANNEX IV

Detailed results of the goodness of fit tests

Annex IV. Detailed results of the goodness of fit tests for the 20 variables with available observed data series, before and after removing the insensitive parameters.

VARIABLES	**n**	**Results for calibration period before removing insensitive parameters**		**Results after removing insensitive parameters**	
		MAPE (%)	**RMSE (%)**	**MAPE (%)**	**RMSE (%)**
Resident population	16	4.30	5.45	4.30	5.45
Births	12	6.22	5.62	6.22	5.62
Inmigration	16	26.18	23.384	26.18	23.384
Emigration	15	32.70	31.65	32.70	31.65
Tourist equivalent population	16	9.52	12.03	9.52	12.03
Tourist accommodation capacity	16	7.29	9.4	7.29	9.4
Occupancy rate	16	8.71	10.84	8.71	10.84
Tourist employment	13	5.39	6.63	5.39	6.63
Houbara habitat	3	0.98	1.53	0.98	1.53
Egyptian vulture population	13	4.54	5.08	4.54	5.08
Urban built-up	16	2.34	2.84	2.34	2.84
Tracks	3	1.06	1.73	1.06	1.73
Roads	3	0.71	1.05	0.71	1.05
Active crops area	15	10.14	11.40	10.14	11.40
Irrigated crops area	15	11.76	13.70	11.76	13.70
Active gavias area	15	10.49	11.55	10.49	11.55
Natural vegetation area	3	0.28	0.45	0.28	0.45
Golf courses area	15	10.01	24.45	10.01	24.45
Vehicles fleet	12	4.57	4.15	4.57	4.15
Electric energy consumption	14	4.98	7.14	4.98	7.14

n: Number of observed data.

ANNEX V

Abbreviations

AP	Action Plan of the Fuerteventura Biosphere Reserve
BAU	Business as Usual
BRs	Biosphere Reserves
CO_2pc	Per capita CO_2 emissions
ear	Ratio between tourist accommodation and resident population
Evp	Egyptian vulture population
fin	Fodder importation needs proportion
FSM	Fuerteventura Biosphere Reserve sustainability model
gap	Active gavias proportion
GDP	Gross domestic product
hhp	Houbara habitat proportion
hqp	High quality vegetation proportion
LAC	Limit of acceptable change
li	Landscape indicator
MAPE	Mean absolute percentage error
MC	Monte Carlo simulations
NGP	Net grazing proportion
NRMSE	Normalised root-mean-squared error
OAT	One factor at a time
oi	Overgrazing indicator
PEpc	Per capita primary energy consumption
SA	Sensitivity analysis
SD	System dynamics
SDMs	System dynamic models
SER	Share of renewable energy
SES	Socio-ecological systems
$S_{i,j}$	Sensitivity index
SWOT	Matrix of the main strengths, weaknesses, opportunities and threats
TRD	Canary Islands Tourism Regulation Directives
tures	Ratio of tourists to residents
U^C	Fraction of the mean-square error due to unequal covariation
U^M	Fraction of the mean-square error due to unequal mean
U^S	Fraction of the mean-square error due to unequal variance
VC_i	Variation coefficient of the target model variable *i*