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Tetrahedron
Tetrahedron 60 (2004) 3359–3373

# Dihydrofurocoumarin and dihydrofurodihydropyrid-2-one derivatives via palladium catalysed cascades involving aryl/heteroaryl/vinyl iodides and allene followed by acid catalysed cyclisation

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Received 17 October 2003; revised 16 February 2004; accepted 25 February 2004

**Abstract**—Mono 3-(2′-arylallyl) derivatives of 4-hydroxycoumarin **1a**,**b**, 4-hydroxy-6-methyl-pyran-2-one (**3**) and 6-hydroxy-1,4-dimethyl-1,2-dihydropyrid-2-one-3-carbonitrile (**4**) are produced in 3-component cascades involving aryl/heteroaryl/vinyl iodides and allene (1 atm) using $Pd(PPh_3)_4/Cs_2CO_3$/MeCN/80 °C or $Pd_2(dba)_3$/tris(2-furyl)phosphine/$K_2CO_3$/DMF/80 °C as the catalyst system. 4-Hydroxy-2-quinolone (**2**) afforded a mixture of mono- and bis-allylation products under these conditions. Mono C-allylation products **5a**–**e** and **15a**–**e** undergo facile acid catalysed cyclisation to afford dihydrofurocoumarins **11a**–**e** and dihydrofurodihydropyrid-2-ones **16a**–**e** in good overall yield.


## 1. Introduction

π-Allylpalladium (II) species are versatile intermediates for organic synthesis and can be generated from Pd(0) and a wide range of allylic substrates including halides, carbonates, acetates, esters, ethers, alcohols, phosphates, amines, sulfones and nitro compounds.[1,2] The generation of π-allylpalladium (II) species from allenes is also well documented.[3] We[4] and others[5] have generated a wide variety of π-allylpalladium (II) species from allenes and aryl/heteroaryl/vinyl halides or triflates. These versatile intermediates undergo attack by a wide range of nucleophiles[4] of which stabilised carbanions, such as malonate, and heteroatom centred nucleophiles, such as amines, N-deprotonated-amides, sulphonamides, ureas and alkoxides and thiolates, are the most widely employed. Previously we have reported the C-dienylation of active methylene pronucleophiles[6] and the O-dienylation of phenols and hydroxyisoquinoline[7] employing allene as the π-allyl precursor. As part of a search for novel nucleophiles for π-allylpalladium (II) species we have investigated the nucleophilicity of heterocyclic scaffolds having an enolic system. Herein, we report the use of the heterocyclic enols 4-hydroxycoumarins **1a**,**b**, 4-hydroxy-2-quinolone (**2**), 4-hydroxy-6-methyl-pyran-2-one (**3**), and 6-hydroxy-1,4-dimethyl-1,2-dihydropyrid-2-one-3-carbonitrile (**4**) as novel nucleophiles for π-allylpalladium (II) species generated in situ from allene (1 atm) and aryl/heteroaryl/vinyl iodides (Scheme 2).

*C*-Allyl-4-hydroxycoumarins are important intermediates in the synthesis of dihydrofurocoumarins. This nucleus occurs in a number of natural products[8] and exhibits a range of biological properties including anticoagulant, insecticidal, anthelmintic, hypnotic, antifungal, phytoalexin and HIV protease inhibition.[9] 3,3-Diallylquinolines are also core components of a range of natural products.[10] 3-Allylation of 4-hydroxycoumarin is normally achieved by Claisen rearrangement of *O*-allyl derivatives[11] or by direct base induced allylation with a suitable allyl precursor.[12] A potential problem with the former methodology is the requirement of vigorous reaction conditions, while the latter methodology may lack regioselectivity and thus produce a mixture of *C*-allyl and *O*-allyl products. Both approaches are constrained by the lack of more complex allylating agents. The implementation of Scheme 2 opens up a rich vein of novel allylic species.

*Keywords*: Allylpalladium; Nucleophiles; Allylation; Hydroxycoumarins; Hydroxyquinolones; Pyrones; Claisen rearrangement; Cyclisation.
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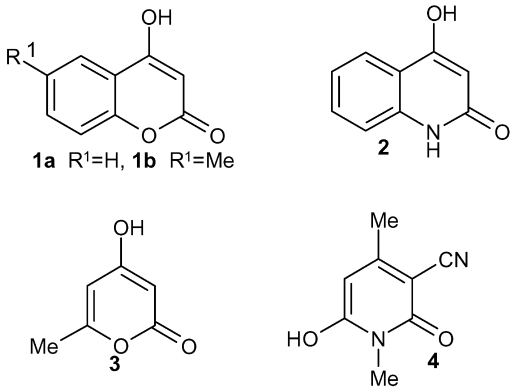
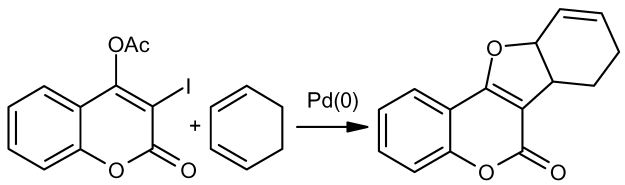
doi:10.1016/j.tet.2004.02.049




Dihydrofurocoumarins have been synthesised by a number of methods including acid catalysed[11b] and palladium catalysed[11a] cyclisation of 3-allyl-4-hydroxycoumarins, oxidative addition of 4-hydroxycoumarin and alkenes or phenylacetylene in the presence of ceric (IV) ammonium nitrate (CAN),[13] manganese (III) acetate hydrate (MAH),[14] silver (I) carbonate/celite[15] and $BF_3$.[16] The reaction of 4-hydroxycoumarins with alkenes or alkynes frequently suffer from poor regiselectivity giving mixtures of angular and linear products. In our case (vide infra), only angular products were obtained. Recently dihydrofurocoumarins have been synthesised by palladium catalysed annulation of 1,3-dienes with *o*-iodoacetoxycoumarins (Scheme 1).[17]




**Scheme 1.**

## 2. Results and discussion

### 2.1. 4-Hydroxycoumarins (1a,b), 4-hydroxy-2-quinolone (2) and 4-hydroxy-6-methyl-pyran-2-one (3) as nucleophiles

Initially we surveyed the effect of several combinations of catalyst, base, solvent and concentration on the 3-component cascade using **1a** as substrate (Table 1). This survey identified $Pd(PPh_3)_4$ (5 mol%) and $Cs_2CO_3$ (2.0 mol equiv.) in MeCN (20 ml/mmol ArI) at 80 °C (Table 1, entry 3) as an efficient combination. The concentration of the reaction mixture has a significant effect on product formation. Thus the use of 20 ml MeCN/mmol ArI gives the mono C-allylation product **5a** (Table 1, entry 3), whilst higher concentrations give rise to a 1:1 mixture of mono- and bis-C-allylation products (Table 1, entry 2), leaving unreacted nucleophile. The mono C-allylation product **5a** could not be isolated as it appears to exist as a mixture of free OH compound and its cesium salt which was insoluble in chloroform. Formation of mono-allyl products was assessed from the $^1$H NMR spectra of the reaction mixtures in deuterated dimethyl sulfoxide which exhibit characteristic resonances for olefinic protons at $\delta$ 4.8 and 5.3 and for the methylene protons next to olefinic carbon at $\delta$ 3.7. Washing the crude reaction mixture with dilute HCl or acetic acid resulted in partial cyclisation to give **11a** which was evidenced in the $^1$H NMR spectra ($CDCl_3$) by the appearance of new AB signals for the methylene protons next to the tetrasubstituted carbon ($\delta$ 3.35) and a singlet for the methyl group ($\delta$ 1.9).

It was convenient to treat the crude product with TFA in $CHCl_3$ at room temperature for 2–3 h to effect complete cyclisation to **11a**. The allylation–cyclisation can be carried out as a one-pot process (TFA, MeCN, 4–5 h), but the isolated yield was lower. The scope and limitations of the 2-step process were then explored employing a range of aryl/heteroaryl/vinyl iodides (Table 2). The presence of an electron withdrawing group in the aryl iodide suppresses cyclisation of **5** to **11** (Scheme 2) by destabilising the intermediate carbocation. This effect, as expected, is general and allows easy isolation of the mono-allylation products (Table 3). A general survey was carried out employing **1a**,**b** and **3** as pronucleophiles and a range of aryl iodides bearing inductive electron withdrawing groups and/or weak mesomeric donors (Table 3). The C-allylation products **5f–j**, **6a–e** and **12a–d** thus obtained did not undergo cyclisation on work-up in aq. acidic solution or even upon treatment with TFA in chloroform which confirms the considerable carbocation character involved in the cyclisation. Under acidic conditions the protonation of the *N*-atom of the pyridyl ring of mono-allyl products **5i** and **6d** (Table 3) has a similar destabilizing effect.

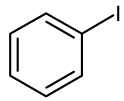
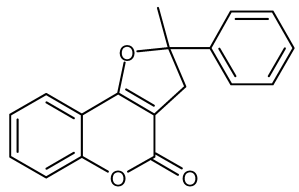
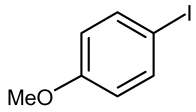
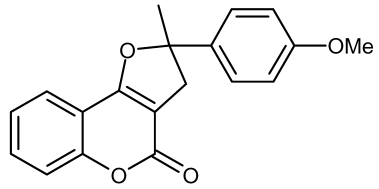
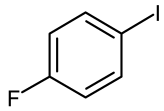
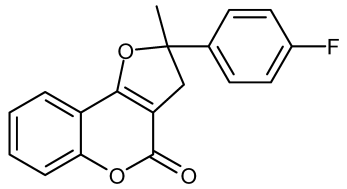
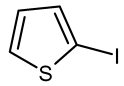
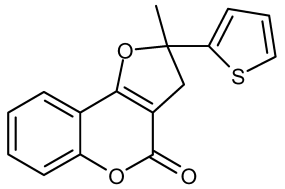
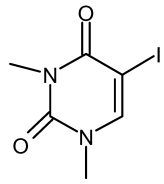
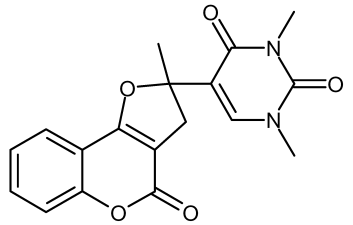
4-Hydroxy-2-quinolone (**2**) afforded a mixture of mono- and bis-C-allylation products **7** and **9**, respectively, under the same reaction conditions applied for the mono-C-allylation

**Table 1**. Effect of catalyst, base and solvent on the C-allylation of heterocyclic nucleophiles (NuH)[a]

| Entry | NuH | Catalyst system[b] | Base | Solvent (ml) | Temperature (°C) | Mono/bis[c] |
|---|---|---|---|---|---|---|
| 1 | **1a** | $Pd(PPh_3)_4$ | $Cs_2CO_3$ | Toluene (20) | 110 | 1:1[d] |
| 2 | | $Pd(PPh_3)_4$ | $Cs_2CO_3$ | MeCN (10) | 80 | 1:1 |
| 3 | | $Pd(PPh_3)_4$ | $Cs_2CO_3$ | MeCN (20) | 80 | 100:0 |
| 4 | **2** | $Pd(PPh_3)_4$ | $Cs_2CO_3$ | MeCN (20) | 80 | 1:2 |
| 5[e] | | $Pd_2(dba)_3$/TFP | $K_2CO_3$ | DMF (10) | 60 | 0:100 |
| 6 | **3** | $Pd(PPh_3)_4$ | $Cs_2CO_3$ | MeCN (20) | 80 | 100:0 |
| 7 | **4** | $Pd_2(dba)_3$/TFP | $K_2CO_3$ | DMF (10) | 80 | 100:0 |

[a] All reactions employed *p*-$MeOC_6H_4I$ (1.0 mmol), nucleophiles **1–4** (1.2 equiv.), allene (1 atm), base (2.0 mol equiv.) in a Schlenk tube for 20–24 h.
[b] 5 mol% Pd and 10–20 mol% phosphine ligand were used.
[c] Ratio of mono- and bis-allyl products were determined by $^1$H NMR.
[d] Conversion was 25%.
[e] 2.1 equiv. Ar–I was used.

**Table 2**. C-Allylation–cyclisation of 4-hydroxycoumarin[a]

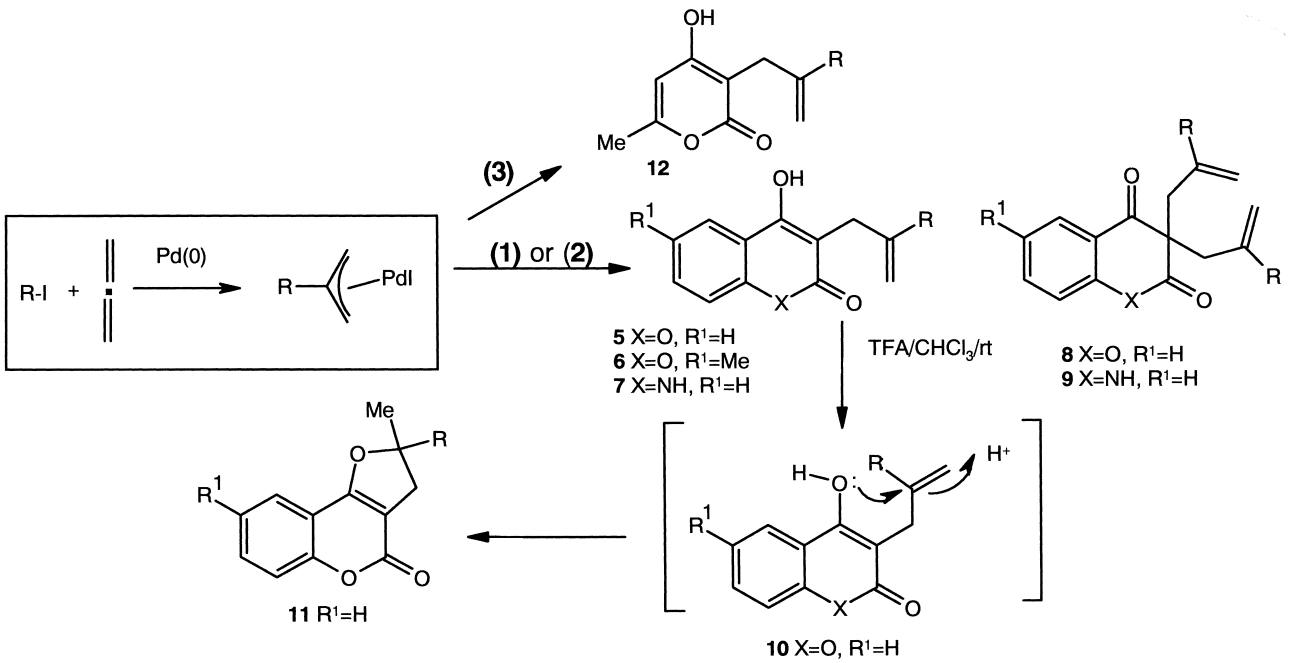
| Entry | R–I | Product **11a–e** | Yield(%)[b] |
|---|---|---|---|
| 1 |  |  **11a** | 62 |
| 2 |  |  **11b** | 65 |
| 3[c] |  |  **11c** | 54 |
| 4 |  |  **11d** | 53 |
| 5 |  |  **11e** | 71 |

[a] All reactions employed RI (1.0 mmol), 4-hydroxycoumarin (1.1 equiv.), allene (1 atm) in a Schlenk tube in presence of $Pd(PPh_3)_4$ (5 mol%) and $Cs_2CO_3$ (2.0 mol equiv.) in MeCN (20 ml) at 80 °C for 20 h. The mixture was then cooled, excess allene released, the mixture filtered and the filtrate evaporated. The residue was suspended in $CHCl_3$, the pH adjusted to 2–3 with TFA and the mixture stirred at room temperature for 2–3 h.
[b] Isolated overall yield for the two steps.
[c] Cyclisation carried out at 50 °C for 2 h.

of 4-hydroxycoumarin (Table 1, entry 4). Using 2.1 equivalent of aryl iodide gave only the bis-C-allylation product (Table 1, entry 5) and several further examples of bis-C-allylation were prepared using $Pd_2(dba)_3$ (2.5 mol%), tris(2-furyl)phosphine (10 mol%), $K_2CO_3$ (2.0 mol equiv.) in DMF at 60 °C (Table 4). The anomalous behaviour of 4-hydroxy-2-quinolone is not fully understood, but is clearly related to the reactivity of the two anions **13** and **14** generated from the mono-allylation products **5** and **7** (Scheme 3). The negative charge of the anion **13** is delocalised over the adjacent carbonyl groups whilst the analogous anion **14** from **7** is less effectively stabilized since nitrogen is less electronegative than oxygen (Scheme 3) and amide resonance of **14** is also important.

### 2.2. 6-Hydroxy-1,4-dimethyl-1,2-dihydropyrid-2-one-3-carbonitrile (4) as nucleophile

Construction of the dihydrofuro[2,3-*b*] pyridinone substructure is as important synthetic issue as this unit occurs in cladobotryal,[18] a potent antifungal and antibacterial agent and in psoralene,[19] a drug for the treatment of skin diseases. We therefore focused on the heterocycle **4** as a potential pronucleophile for our π-allyl intermediates. The reaction of aryl/heteroaryl/vinyl iodides (RI), allene (1 bar) and the nucleophile (**4**) (Scheme 4) was studied with a catalyst system comprising $Pd_2(dba)_3$ (2.5 mol%), tris(2-furyl)-phosphine (10 mol%) and $K_2CO_3$ (2.0 mol equiv.) in DMF at 80 °C for 20 h. The results are shown in Table 5. As encountered before intermediates **15a–e** could not be isolated. Again they appear to exist as a mixture of the free OH compound and the potassium salt and washing the crude product with dilute HCl or acetic acid resulted in a partial cyclisation of the intermediate **15** to **16**. We therefore instituted a second step (TFA, $CHCl_3$, room temperature, 2 h) which gave the cyclised products **16a–e** (Table 5). The cyclisation of the intermediate is also possible as a one-pot process but it requires longer reaction time and results in poor yield. From the mechanistic point of view, the C-allylation of nucleophiles




**Scheme 2.**

**Table 3**. *C*-Allylated 4-hydroxycoumarins and 4-hydroxy-6-methyl-pyran-2-one[a]

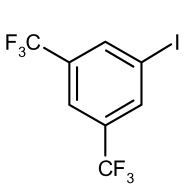
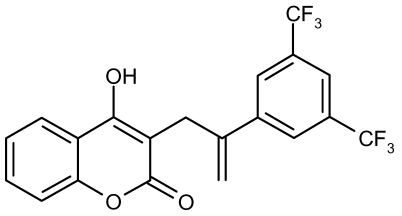
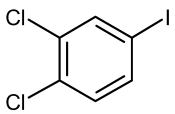
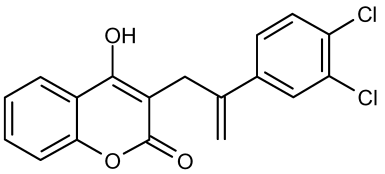
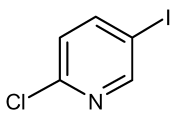
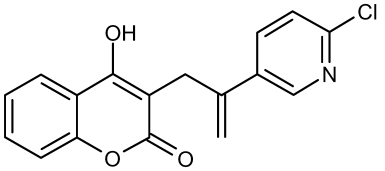
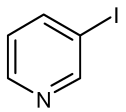
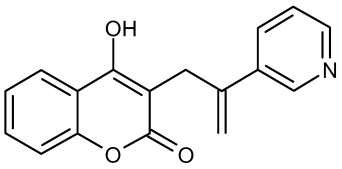
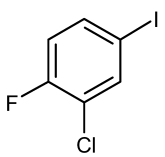
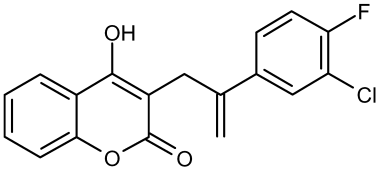
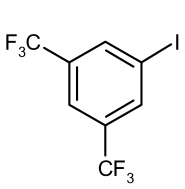
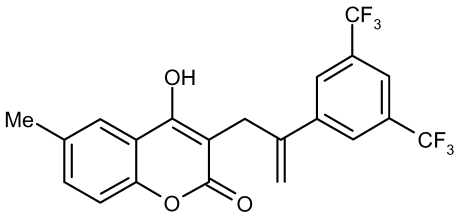
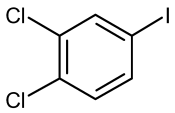
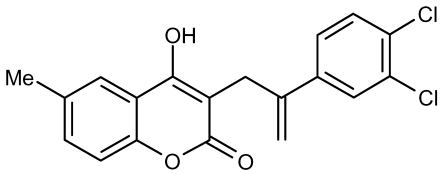
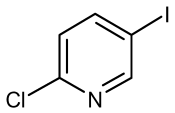
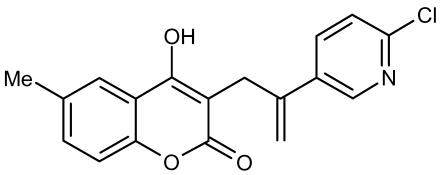
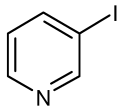
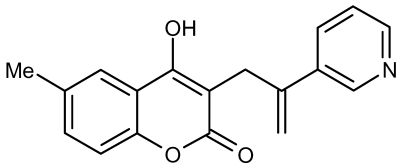
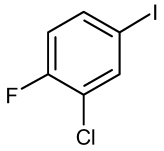
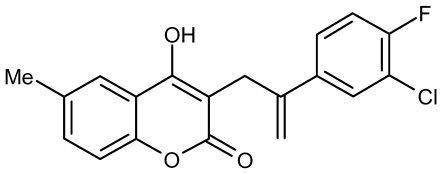
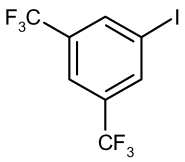
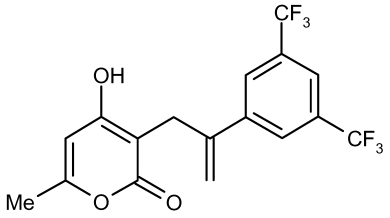
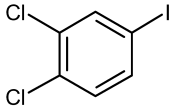
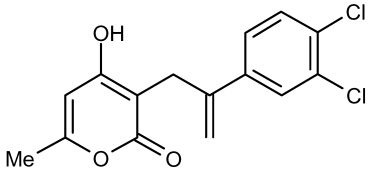
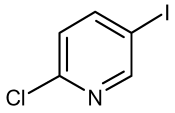
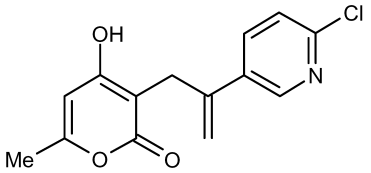
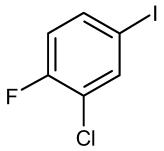
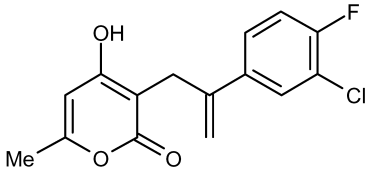
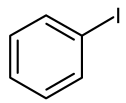
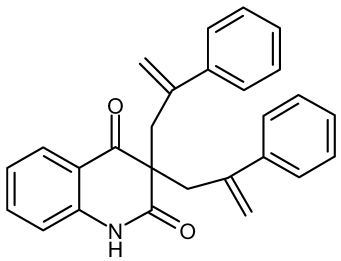
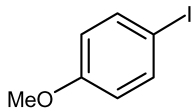
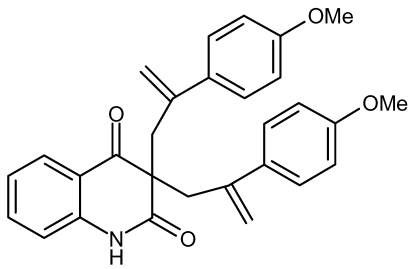
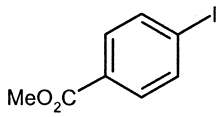
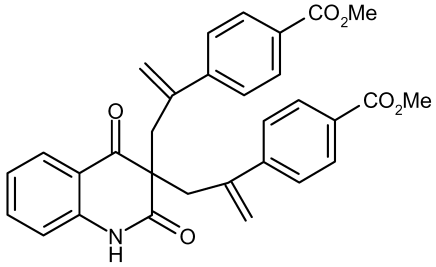
| Entry | NuH | Ar–I | Products | | Yield (%)[b] |
|---|---|---|---|---|---|
| 1 | **1a** |  |  | **5f** | 97 |
| 2 | |  |  | **5g** | 91 |
| 3 | |  |  | **5h** | 91 |
| 4 | |  |  | **5i** | 65 |
| 5 | **1b** |  |  | **5j** | 92 |

**Table 3** (*continued*)

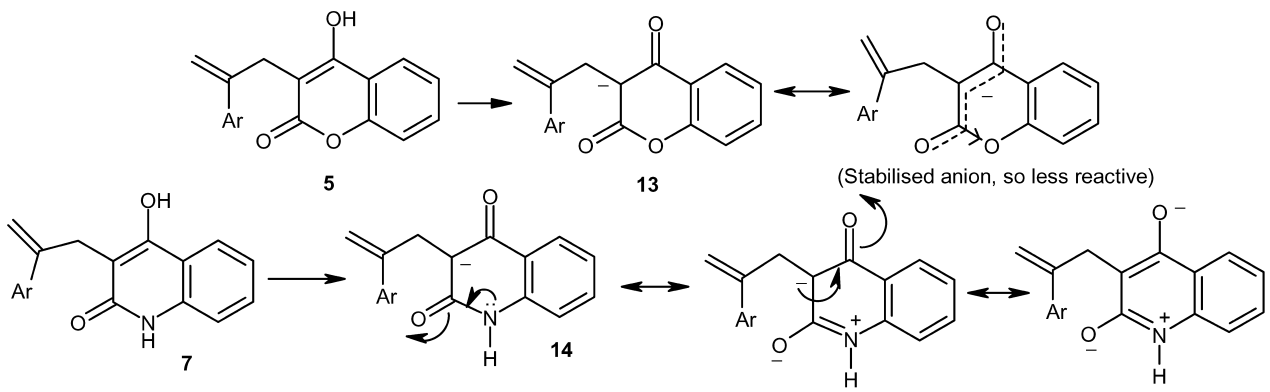
| Entry | NuH | Ar–I | Products | | Yield (%)[b] |
|---|---|---|---|---|---|
| 6 | |  |  | **6a** | 69 |
| 7 | |  |  | **6b** | 75 |
| 8 | |  |  | **6c** | 94 |
| 9 | |  |  | **6d** | 66 |
| 10 | |  |  | **6e** | 62 |
| 11 | **3** |  |  | **12a** | 67 |
| 12 | |  |  | **12b** | 72 |
| 13 | |  |  | **12c** | 95 |
| 14 | |  |  | **12d** | 71 |

[a] All reactions employed ArI (1.0 mmol), 4-hydroxycoumarins **1a**,**b** or 4-hydroxy-6-methyl-pyran-2-one (**3**) (1.10 equiv.), allene (1 atm) in a Schlenk tube in the presence of $Pd(PPh_3)_4$ (5 mol%) and $Cs_2CO_3$ (2.0 mol equiv.) in MeCN (20 ml) at 65 °C for 20 h.
[b] Isolated yield.

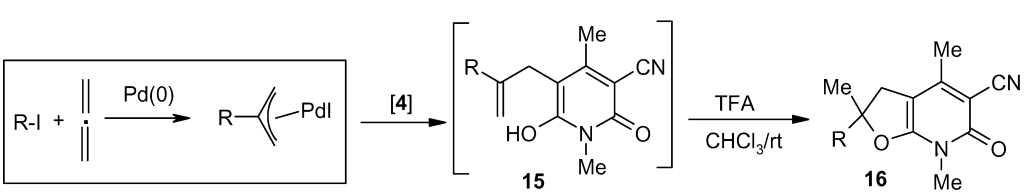
**Table 4**. Bis-*C*-allylated of 4-hydroxy-2-quinolone[a]

| Entry | Ar–I | Products **9a–c** | Yield (%)[b] |
|---|---|---|---|
| 1 |  |  **9a** | 56 |
| 2 |  |  **9b** | 41 |
| 3 |  |  **9c** | 75 |

[a] All reactions employed Ar–I (2.1 mmol), allene (1 atm) and 4-hydroxy-2-quinolone (**2**) (1.0 equiv.) in the presence of $Pd_2(dba)_3$ (2.5 mol%), tris(2-furyl)phosphine (10 mol%) and $K_2CO_3$ (2.0 mol equiv.) in DMF (10 ml) at 60 °C for 20 h.
[b] Isolated yield.

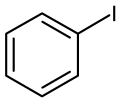
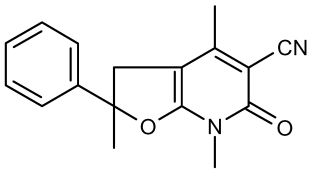
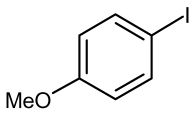
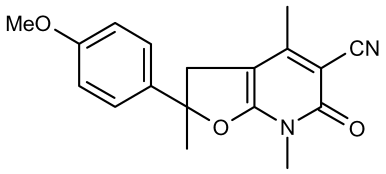
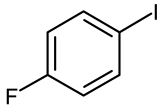
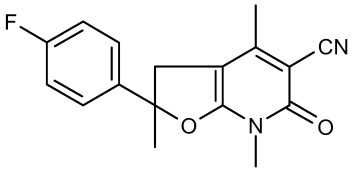
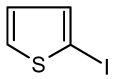
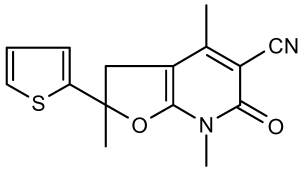
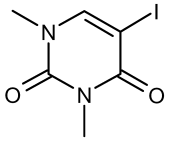
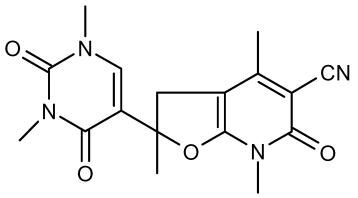



**Scheme 3.**




**Scheme 4.**

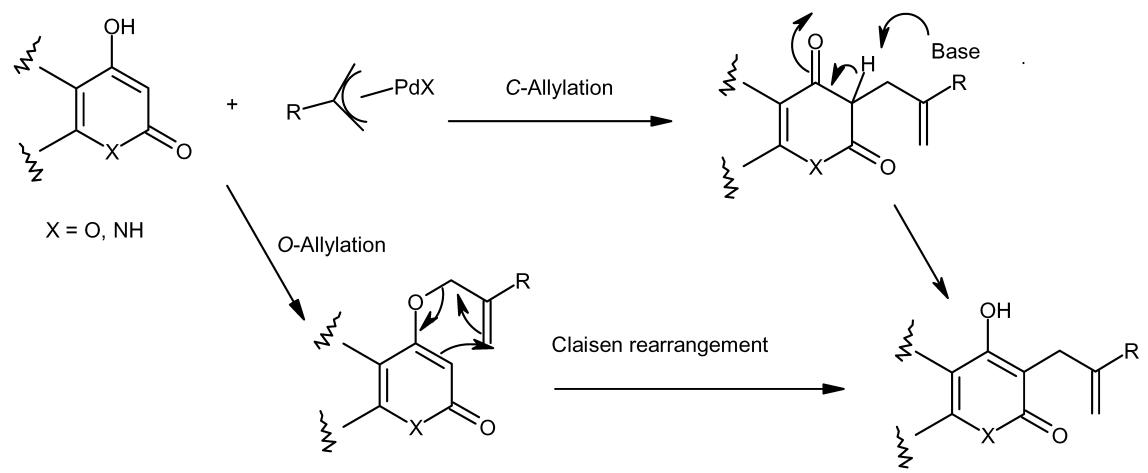
**Table 5**. C-Allylation–cyclisation of 6-hydroxy-1,4-dimethyl-1,2-dihydropyrid-2-one-3-carbonitrile (**4**)[a]

| Entry | RI | Products | | Yield (%)[b] |
|---|---|---|---|---|
| 1 |  |  | **16a** | 52 |
| 2 |  |  | **16b** | 55 |
| 3 |  |  | **16c** | 35 |
| 4 |  |  | **16d** | 50 |
| 5 |  |  | **16e** | 52 |

[a] All reactions employed RI (1.0 mmol), pyridone **4** (1.1 equiv.) and allene (1 atm) in presence of $Pd_2(dba)_3$ (2.5 mol%), tris(2-furyl)phosphine (10 mol%) and $K_2CO_3$ (2.0 mol equiv.) in DMF (10 ml) at 80 °C in a Schlenk tube for 20 h. The crude material was suspended in $CHCl_3$ and treated with TFA (pH=2–3) and left for 2–3 h with stirring.

[b] Isolated yield.

**1**–**4** could arise by direct C-allylation or by O-allylation followed by Claisen rearrangement (Scheme 5). A few examples of the palladium catalysed alkylation of phenols with allyl carbonates, acetates or related π-allylpalladium (II) precursors have been reported.[20] Normally, Claisen rearrangement requires heating above 100 °C but we could not rule out this route as Claisen, and other [3,3]-sigmatropic, rearrangements have been reported to be catalysed by palladium[21,22] under mild conditions.




**Scheme 5.**

## 3. Conclusion

4-Hydroxycoumarins **1a**,**b**, 4-hydroxy-2-quinolone (**2**), 4-hydroxy-6-methyl-pyran-2-one (**3**) and pyridone (**4**) have been developed as novel pronucleophiles for palladium-catalysed cascades involving aryl/heteroaryl/vinyl iodides and allene. Mono-C-allylation of **1a**,**b**, **3** and **4** proceeded in the presence of $Pd(PPh_3)_4/Cs_2CO_3$/MeCN (20 ml/mmol RI)/80 °C and $Pd_2(dba)_3$/tris(2-furyl)-phosphine/$K_2CO_3$/DMF/80 °C respectively. The mono-allylation products **5a**–**e** and **15a**–**e** could not be isolated as they comprised mixtures of salts of cesium or potassium and free OH compounds. Treatment of these mixtures with TFA in $CHCl_3$ at room temperature effects cyclisation to afford dihydrofurocoumarin and dihydro-furo-dihydropyrid-2-one derivatives **11a**–**e** and **16a**–**e** respectively. Allylation of **2**, under the same conditions as for **1a**,**b** and **3**, gives a 1:2 mixture of mono- and bis-allyl products **7** and **9**, respectively. Bis-allylation products **9a**–**c** were prepared by employing an excess of aryl iodide (2.1 equiv.).

## 4. Experimental

### 4.1. General technical data

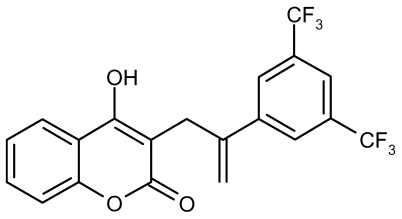
Commercially available reagents were used without further purification but, where appropriate, solvents were purified according to procedures given in *Purification of Laboratory Chemicals*, Perrins, D. D.; Armarego, W. L. F.; Perrin, D. R. Permagon Press, 1980. Nucleophile **4** was a gift from BASF. Flash column chromatography was performed on Merck silica gel 60 (230–400 mesh). $R_f$ values were determined by thin layer chromatography (TLC) on Merck silica gel 60 $F_{254}$ and spots were visualised with UV light (254 nm). The term petroleum ether refers to the fraction with bp 40–60 °C and the term ether refers to diethyl ether. Melting points were determined on a Kofler hot stage apparatus and are uncorrected.

Microanalyses were obtained using a Carlo-Erba Model 1106 instrument. Proton nuclear magnetic resonance ($^1$H NMR) spectra experiments were determined at 300 MHz on a Bruker DPX300 spectrometer. Chemical shifts are reported in parts per million ($\delta$) downfield from tetra-methylsilane as internal standard and coupling constants are given in Hertz (Hz). Except where otherwise stated, spectra were determined in deuteriochloroform. The following abbreviations are used; s=singlet, d=doublet, t=triplet, q=quartet, dd=double doublet, dt=double triplet, td=triple doublet, m=multiplet, br=broad and brs=broad singlet. $^{13}$C NMR spectra were recorded with a Bruker DPX300 (75 MHz) and chemical shift values are reported in parts per million (ppm) relative to $CDCl_3$ ($\delta$=77.0). Mass spectra were obtained on a VG Autospec instrument at 70 eV using electron impact (EI) and on a LCT Micromas using electrospray (ES) techniques. Infrared spectra were recorded on a Perkin–Elmer FT-IR spectrometer either by a film technique on sodium chloride discs by spreading DCM solution on the discs or for solids using a Combi pod. The samples for the film technique were prepared by dissolving a small amount of compound in DCM, pipetting the solution on to a sodium chloride plate and allowing the DCM to evaporate.

### 4.2. General procedure for C-allylation of 4-hydroxy-coumarins (1a,b) and 4-hydroxy-6-methylpyran-2-one (3)

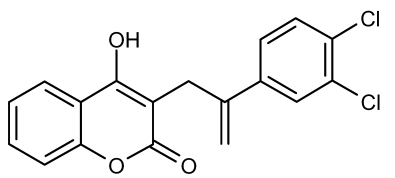
A mixture of aryl/heteroaryl/vinyl iodide (1.0 mmol, 1.0 equiv.), 4-hydroxycoumarin **1a** (0.18 g, 1.10 mmol, 1.10 equiv.), or **1b** (0.21 g, 1.10 mmol, 1.10 equiv.) or 4-hydroxypyrone **3** (0.15 g, 1.10 mmol, 1.10 equiv.), tetrakis(triphenyl)phosphinepalladium (0.06 g, 5.0 mol%) and cesium carbonate (0.65 g, 2.0 mol equiv.) in MeCN (20 ml) was stirred for 15 min in a Schlenk tube. The mixture was then degassed, frozen, evacuated and charged with allene (1 bar). After warming to room temperature it was heated at 65–80 °C in an oil bath for 16 h. The mixture was then cooled to room temperature, excess allene vented, the mixture was treated with 5% (w/v) aq. HCl (15 ml) and the mixture was extracted with chloroform (3×10 ml). The combined organic layer was washed with water (20 ml), dried ($MgSO_4$) and the filtrate concentrated under reduced pressure. The residue was either purified by column chromatography or directly used for cyclisation.

#### 4.2.1. 3-{2-[3,5-Bis(trifluoromethyl)phenyl]prop-2-en-1-yl}-4-hydroxy-2*H*-chromen-2-one (5f).



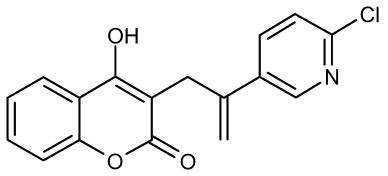

Column chromatography eluting with 7:3 v/v petroleum ether–ethyl acetate gave the product (97%) as a colourless solid, which crystallized from acetone as colourless needles, mp 183–185 °C. (Found: C, 57.60; H, 2.75; $C_{20}H_{12}O_3F_6$ requires C, 57.65; H, 2.95%); $\delta_H$ (300 MHz, DMSO-$d_6$) 3.75 (2H, s, =C–$CH_2$), 5.09 (1H, s, $CH_2$=), 5.62 (1H, s, $CH_2$=), 7.32–7.38 (2H, m, ArH), 7.61 (1H, m, ArH), 7.95 (1H, d, $J$=7.7 Hz, ArH) 8.01 (1H, s, ArH), 8.2 (2H, s, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 29.1 ($CH_2$), 101.9, 115.7, 116.4, 116.5, 121.3, 123.7, 124.2, 126.9, 123.7 (q, $JC-^{19}F$=272.9 Hz, $CF_3$), 130.7 (q, $JC-^{19}F$=32.7 Hz, $C-CF_3$), 132.3, 142.2, 143.8, 152.5, 161.6 and 163.0 (CO); $m/z$ (ES) 415 (100%, $M^+$), 343 (15), 175 (84) and 102 (33); $\nu_{max}$/cm$^{-1}$ (film) 3944, 3691, 3054, 2987, 2685, 2305, 1667, 1633, 1572, 1497, 1421, 1332, 1265, 1169, 1075, 965, 896, 739, 643, and 549.

#### 4.2.2. 3-{2-[3,4-Dichlorophenyl]prop-2-en-1-yl}-4-hydroxy-2*H*-chromen-2-one (5g).



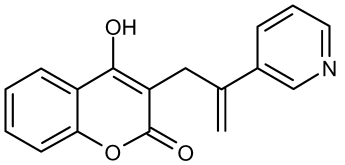
Column chromatography eluting with 1:1 v/v petroleum ether–ethyl acetate gave the product (91%) as a colourless solid, mp 174–176 °C. (Found: C, 62.20; H, 3.65, Cl, 20.35; $C_{18}H_{12}Cl_2O_3$ requires C, 62.25; H, 3.50, Cl, 20.40%) $\delta_H$ (500 MHz, DMSO-$d_6$) 3.66 (2H, s, =C–$CH_2$), 4.93 (1H, s, $CH_2$=), 5.45 (1H, s, $CH_2$=), 7.35–7.39 (2H, m, ArH), 7.55 (1H, d, $J$=8.2 Hz, ArH), 7.61–7.63 (2H, m, ArH), 7.79 (1H, s, ArH), 7.96 (1H, d, $J$=7.8 Hz, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 29.0 ($CH_2$), 102.1, 113.6, 116.5, 116.6, 123.7, 124.2, 126.5, 128.1, 130.3, 130.7, 131.4, 132.3, 141.8, 142.3, 152.5, 161.5 and 163.0 (CO); $m/z$ (ES) 352 (11%, $M^+$, $^{37}Cl$ and $^{37}Cl$), 350 (66, $M^+$, $^{37}Cl$ and $^{35}Cl$) and 348 (100, $M^+$, $^{35}Cl$ and $^{35}Cl$); $\nu_{max}/cm^{-1}$ (film) 3126, 1666, 1630, 1496, 1453, 1398, 1330, 1292, 1202, 1163, 1111, 1070, 1025, 961, 905, 878, 823, 759, 718, 683, 647 and 457.

#### 4.2.3. 3-[2-(6-Chloropyridin-3-yl)prop-2-en-1-yl]-4-hydroxy-2*H*-chromen-2-one (5h).



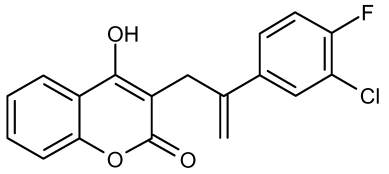

Column chromatography eluting with 3:7 v/v petroleum ether–ethyl acetate afforded the product (91%), as a colourless amorphous solid, mp 170–172 °C. (Found: C, 65.05; H, 4.35; N, 4.40; $C_{17}H_{12}O_3NCl$ requires C, 65.10; H, 4.15; N, 4.45%); $\delta_H$ (300 MHz, DMSO-$d_6$) 3.65 (2H, s, =C–$CH_2$), 4.95 (1H, s, $CH_2$=), 5.5 (1H, s, $CH_2$=), 7.33–7.39, (2H, m, ArH), 7.52 (1H, d, $J$=8.3 Hz, ArH), 7.6 (1H, t, $J$=8.2 Hz, ArH), 7.95 (1H, d, $J$=7.8 Hz, ArH), 8.0 (1H, dd, $J$=8.3, 2.5 Hz, ArH), 8.6 (1H, d, $J$=2.5 Hz, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 29.0 ($CH_2$), 101.9, 114.1, 116.5, 116.6, 123.7, 124.1, 124.3, 132.3, 136.0, 137.3, 140.7, 147.5, 149.5, 152.5, 161.7 and 163.0 (CO); $m/z$ (ES) 316 (33%, $M^+$, $^{37}Cl$) and 314 (100, $M^+$, $^{35}Cl$); $\nu_{max}/cm^{-1}$ (film) 3189, 1666, 1631, 1573, 1554, 1497, 1474, 1452, 1431, 1399, 1366, 1328, 1291, 1202, 1162, 1148, 1110, 1072, 1017, 915, 824, 685, 516 and 483.

#### 4.2.4. 4-Hydroxy-3-(2-pyridin-3-ylprop-2-en-1-yl)-2*H*-chromen-2-one (5i).



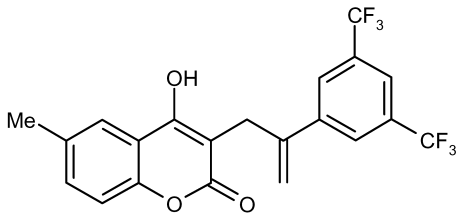

Washed with dichloromethane and crystallised from petroleum ether–ethyl acetate to afford the product (65%) as a colourless amorphous solid, mp 182–184 °C. (HRMS: 280.0959 ($M^+$+H); $C_{17}H_{13}NO_3$ requires 280.0974 ($M^+$+H)); $\delta_H$ (300 MHz, DMSO-$d_6$) 3.69 (2H, s, =C–$CH_2$), 4.94 (1H, s, $CH_2$=), 5.44 (1H, s, $CH_2$=), 7.32–7.42 (3H, m, ArH), 7.61 (1H, t, $J$=8.3 Hz, ArH), 7.95 (2H, d, $J$=7.64 Hz, ArH), 8.5 (1H, d, $J$=4.6 Hz, ArH), 8.75 (1H, s, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 29.1 ($CH_2$), 100.8, 113.1, 116.4, 117.7, 123.6, 123.8, 123.9, 131.8, 133.5, 137.5, 142.4, 147.3, 148.8, 152.7, 163.3, and 163.4 (CO); $m/z$ (ES) 280 (100%, $M^+$+H), and 127 (16); $\nu_{max}/cm^{-1}$ (film) 3043, 2906, 1691, 1610, 1570, 1495, 1456, 1421, 1333, 1283, 1237, 1193, 1166, 1056, 919, 898, 819, 770, 724, 652, 608, 533 and 486.

#### 4.2.5. 3-{2-[3-Chloro-4-fluorophenyl]prop-2-en-1-yl}-4-hydroxy-2*H*-chromen-2-one (5j).



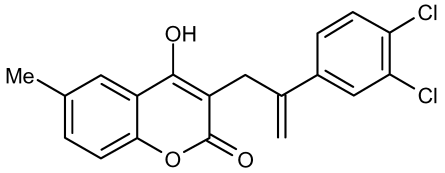

Column chromatography eluting with 1:1 v/v petroleum ether–ether gave the product (92%) as a colourless amorphous solid, mp 175–177 °C. (Found: C, 65.05; H, 3.75; $C_{18}H_{12}O_3F_6$ requires C, 65.35, H, 3.65%); $\delta_H$ (300 MHz, DMSO-$d_6$) 3.65 (2H, s, =C–$CH_2$), 4.86 (1H, s, $CH_2$=), 5.39 (1H, s, $CH_2$=), 7.34–7.44 (3H, m, ArH), 7.56–7.65 (2H, m, ArH), 7.75 (1H, d, $J$=5.2 Hz, ArH), 7.95 (1H, d, $J$=7.5 Hz, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 29.2 ($CH_2$), 102.2, 113.0 (=$CH_2$), 116.5, 116.6, 116.9, 117.1, 123.7, 124.3, 126.8, 126.9, 128.2, 132.3, 139.0, 142.4, 152.5, 161.5 and 163.0 (CO); $m/z$ (ES) 334 (33%, $M^+$, $^{37}Cl$) and 332 (100, $M^+$, $^{35}Cl$); $\nu_{max}/cm^{-1}$ (film) 3167, 2875, 1714, 1664, 1629, 1498, 1454, 1398, 1330, 1262, 1199, 1162, 1111, 1056, 960, 879, 819, 762, and 645.

#### 4.2.6. 3-{2-[3,5-Bis(trifluoromethyl)phenyl]prop-2-en-1-yl}-4-hydroxy-6-methyl-2*H*-chromen-2-one (6a).



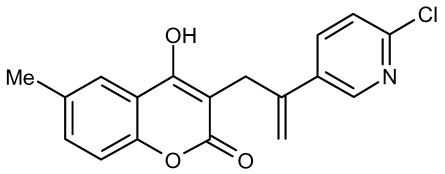

Column chromatography eluting with 1:1 v/v petroleum ether–ethyl acetate afforded the product (67%) as a colourless solid, which crystallized from DCM as colourless needles, mp 165–167 °C. (Found: C, 58.70; H, 3.45; $C_{21}H_{14}O_3F_6$ requires C, 58.9; H, 3.30%); $\delta_H$ (300 MHz, DMSO-$d_6$) 2.36 (3H, s, Me), 3.73 (2H, s, =C–$CH_2$), 5.06 (1H, s, $CH_2$=), 5.62 (1H, s, $CH_2$=), 7.25 (1H, d, $J$=8.4 Hz, ArH), 7.40 (1H, d, $J$=8.4 Hz, ArH), 7.75 (1H, s, ArH), 8.0 (1H, s, ArH), 8.15 (2H, s, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 20.8 (Me), 29.2 ($CH_2$), 101.7, 115.7, 116.1, 116.3, 123.3, 126.9, 130.6, 123.7 (q, $JC-^{19}F$=272.9 Hz, $CF_3$), 130.7 (q, $JC-^{19}F$=32.7 Hz, $C-CF_3$), 133.1, 133.5, 142.3, 143.8, 150.6, 161.6 and 163.1 (CO); $m/z$ (ES) 429 (100%, $M^+$+H), 173 (10), 151 (13) and 103 (26); $\nu_{max}/cm^{-1}$ (film) 3084, 1654, 1627, 1579, 1504, 1430, 1316, 1287, 1209, 1181, 1149, 1121, 1075, 1012, 976, 912, 889, 847, 823, 770, 732, 693, 683, 659, 611, 538 and 465.

#### 4.2.7. 3-[2-(3,4-Dichlorophenyl)prop-2-en-1-yl]-4-hydroxy-6-methyl-2*H*-chromen-2-one (6b).



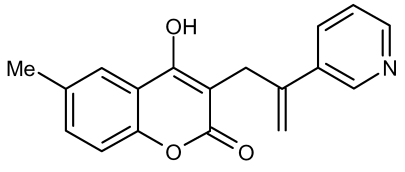

Column chromatography eluting with 1:1 v/v petroleum ether–ethyl acetate afforded the product (75%), which crystallized from dichloromethane as a colourless needles, mp 186–188 °C. (Found: C, 63.25; H, 4.10; Cl, 19.35; $C_{19}H_{14}Cl_2O_3$ requires 63.20; H, 3.90; Cl, 19.60%); $\delta_H$ (300 MHz, DMSO-$d_6$) 2.40 (3H, s, Me), 3.60 (2H, s, =C–$CH_2$), 4.9 (1H, s, $CH_2$=), 5.4 (1H, s, $CH_2$=), 7.28 (1H, d, $J$=8.5 Hz, ArH), 7.4 (1H, d, $J$=8.2 Hz, ArH), 7.5 (1H, d, $J$=8.2 Hz, ArH), 7.6 (1H, d, $J$=8.5 Hz, ArH), 7.7 (1H, s, ArH), 7.9 (1H, s, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 20.8 (Me), 29.0 ($CH_2$), 102.0, 113.6, 116.1, 116.4, 123.3, 126.5, 128.1, 130.3, 130.7, 131.4, 133.1, 133.5, 141.8, 142.4, 150.6, 161.5 and 163.1 (CO); $m/z$ (ES) 365 (11%, $M^+$, $^{37}Cl$ and $^{37}Cl$), 363 (66, $M^+$, $^{37}Cl$ and $^{35}Cl$) and 361 (100, $M^+$, $^{35}Cl$ and $^{35}Cl$); $\nu_{max}/cm^{-1}$ (film) 3282, 2827, 1662, 1627, 1583, 1503, 1421, 1391, 1294, 1202, 1144, 1114, 1065, 1024, 977, 898, 881, 819, 770, 720, 694, 659, 626, 538, 488 and 477.

#### 4.2.8. 3-[2-(6-Chloropyridin-3yl)prop-2-en-1-yl]-4-hydroxy-6-methyl-2*H*-chromen-2-one (6c).



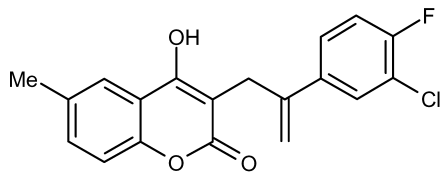

Column chromatography eluting with 3:7 v/v petroleum ether–ethyl acetate afforded the product (94 as a colourless powder, mp 171–173 °C. (Found: C, 65.75; H, 4.8; 4.05; $C_{17}H_{12}ClNO_3$ requires C, 65.95; H, 3.80, N, 4.25%); $\delta_H$ (300 MHz, DMSO-$d_6$) 2.4 (3H, s, Me), 3.65 (2H, s, =C–$CH_2$), 4.95 (1H, s, $CH_2$=), 5.5 (1H, s, $CH_2$=), 7.25 (1H, d, $J$=8.4 Hz, ArH), 7.4 (1H, d, $J$=8.0 Hz, ArH), 7.5 (1H, d, $J$=8.4 Hz, ArH), 7.75 (1H, s, ArH), 8.0 (1H, dd, $J$=8.0, 2.4 Hz, ArH), 8.6 (1H, d, $J$=2.4 Hz, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 20.8 (Me), 29.0 ($CH_2$), 101.8, 114.1, 116.1, 116.4, 123.3, 124.1, 133.2, 133.5, 136.0, 137.3, 140.7, 143.5, 147.5, 149.4, 150.6 and 161.5 (CO); $m/z$ (ES) 331 (33% $M^+$+H, $^{37}Cl$), 329 (100, $M^+$+H, $^{35}Cl$), and 280 (17); $\nu_{max}/cm^{-1}$ (film) 3667, 2924, 1666, 1630, 1583, 1555, 1503, 1475, 1430, 1393, 1367, 1295, 1234, 1200, 1143, 1115, 1064, 1017, 979, 913, 884, 813, 785, 818, 694, 663, 630, 546 and 489.

#### 4.2.9. 4-Hydroxy-6-methyl-3-(2-pyridin-3-ylprop-2-en-1-yl)-2*H*-chromen-2-one (6d).



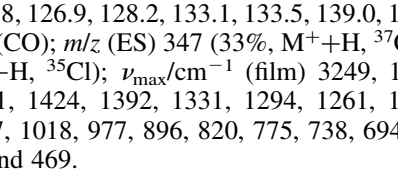

Column chromatography eluting with 1:4 v/v petroleum ether–ethyl acetate afforded the product (63%), which crystallized from ethyl acetate–petroleum ether as a colourless powder, mp 174–176 °C. (HRMS: 294.1123 ($M^+$+H); $C_{18}H_{15}NO_3$ requires 294.1130 ($M^+$+H)); $\delta_H$ (300 MHz, DMSO-$d_6$) 2.4 (3H, s, Me), 3.70 (2H, s, =C–$CH_2$), 5.0 (1H, s, $CH_2$=), 5.55 (1H, s, $CH_2$=), 7.3 (1H, d, $J$=8.3 Hz, ArH), 7.4 (1H, d, $J$=8.3 Hz, ArH), 7.7 (1H, dd, $J$=7.8, 4.7 Hz, ArH), 7.75 (1H, s, ArH), 8.3 (1H, d, $J$=7.8 Hz, ArH), 8.65 (1H, d, $J$=4.7 Hz, ArH), 8.9 (1H, s, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 20.8 (Me), 28.9 ($CH_2$), 101.8, 115.0, 116.1, 116.4, 123.3, 125.2, 133.2, 133.5, 137.6, 137.9, 140.8, 144.0, 145.5, 150.6 and 161.7 (CO); $m/z$ (ES) 294 (100%, $M^+$+H); $\nu_{max}/cm^{-1}$ (film) 3063, 1694, 1630, 1580, 1539, 1494, 1389, 1323, 1280, 1229, 1180, 1144, 1109, 1049, 939, 902, 808, 713, 666, 620, 478, and 464.

#### 4.2.10. 3-[2-(3-Chloro-4-fluorophenyl)prop-2-en-1-yl]-4-hydroxy-6-methyl-2*H*-chromen-2-one (6e).




Column chromatography eluting with 3:2 v/v petroleum ether–ethyl acetate afforded the product (62%), which crystallized from acetone as a colourless needles, mp 181–182 °C. (Found: C, 66.0; H, 4.30; Cl, 10.15; $C_{19}H_{14}ClFO_3$ requires C, 66.20; H, 4.10, Cl, 10.30%); $\delta_H$ (300 MHz, DMSO-$d_6$) 2.5 (3H, s, Me), 3.65 (2H, s, =C–$CH_2$), 4.85 (1H, s, $CH_2$=), 5.4 (1H, s, $CH_2$=), 7.25 (1H, d, $J$=8.4 Hz, ArH), 7.35–7.4 (2H, m, ArH), 7.55 (1H, m, ArH), 7.7–7.75 (2H, m, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 20.8 (Me), 29.2 ($CH_2$), 102.1, 112.9, 116.1, 116.3, 116.8, 117.1, 119.6, 123.3, 126.8, 126.9, 128.2, 133.1, 133.5, 139.0, 142.4, 161.5 and 163.1 (CO); $m/z$ (ES) 347 (33%, $M^+$+H, $^{37}Cl$) and 345 (100, $M^+$+H, $^{35}Cl$); $\nu_{max}/cm^{-1}$ (film) 3249, 1665, 1628, 1583, 1501, 1424, 1392, 1331, 1294, 1261, 1200, 1145, 1116, 1067, 1018, 977, 896, 820, 775, 738, 694, 657, 628, 541, 488 and 469.

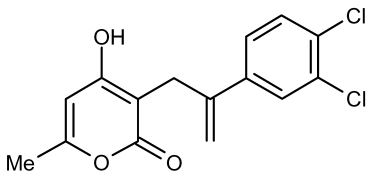
#### 4.2.11. 3-{2-[3,5-Bis(trifluoromethyl)phenyl]prop-2-en-1-yl}-4-hydroxy-6-methyl-2*H*-pyran-2-one (12a).




Column chromatography eluting with the solvent petroleum ether–ethyl acetate 1:1 afforded the product (67%) as a colourless solid, which crystallized from dichloromethane as a colourless needles, mp 166–168 °C. (Found: C, 54.0; H, 3.15; $C_{17}H_{12}O_3F_6$ requires C, 54.0; H, 3.20%); $\delta_H$ (300 MHz, DMSO-$d_6$) 2.15 (3H, s, Me), 3.5 (2H, s, =C–$CH_2$), 5.2 (1H, s, $CH_2$=), 5.60 (1H, s, $CH_2$=), 6.0 (1H, s,

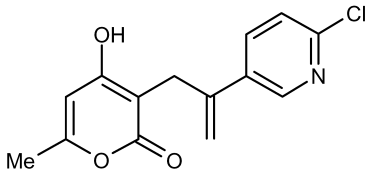
O–C═CH), 8.0 (1H, s, ArH), 8.15 (2H, s, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 19.6 (Me), 28.4 ($CH_2$), 98.1, 100.1, 116.6 (C═$CH_2$), 121.1, 126.8, 123.7 (q, $J$C–$^{19}$F=272.7 Hz, $CF_3$), 130.6 (q, $J$C–$^{19}$F=32.7 Hz, $C$–$CF_3$), 142.7, 143.5, 161.1, 164.8 and 166.7; *m/z* (ES) 380 (100%, $M^+$+H); $\nu_{max}$/cm$^{-1}$ (film) 2617, 1662, 1620, 1560, 1451, 1405, 1378, 1292, 1274, 1180, 1163, 1116, 994, 901, 693, 639, 611, 505 and 466.

#### 4.2.12. 3-[2-(3,4-Dichlorophenyl)prop-2-en-1-yl]-4-hydroxy-6-methyl-2*H*-pyran-2-one (12b).



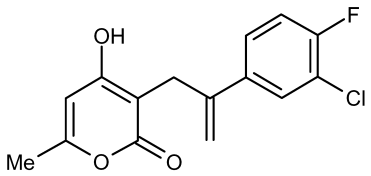

Column chromatography eluting with 1:1 v/v petroleum ether–ethyl acetate afforded the product (73%), which crystallized from ethanol–water as colourless plates, mp 184–186 °C. (HRMS: 311.0240 ($M^+$+H); $C_{15}H_{13}Cl_2O_3$ requires 311.0242 ($M^+$+H)); $\delta_H$ (300 MHz, DMSO-$d_6$) 2.15 (3H, s, Me), 3.4 (2H, s, ═C–$CH_2$), 4.95 (1H, s, $CH_2$═), 5.4 (1H, s, $CH_2$═), 6.0 (1H, S, O–C═CH), 7.5 (1H, d, $J$=8.4 Hz, ArH), 7.6 (1H, d, $J$=8.4 Hz, ArH), 7.75 (1H, s, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 19.7 (Me), 28.3 ($CH_2$), 98.4, 100.1, 114.2, 126.5, 128.1, 130.2, 130.6, 131.3, 141.7, 142.8, 161.0, 164.8 and 166.4 (CO); *m/z* (ES) 315 (11%, $M^+$, $^{37}$Cl and $^{37}$Cl), 313 (66, $M^+$, $^{37}$Cl and $^{35}$Cl) and 311 (100, $M^+$, $^{35}$Cl and $^{35}$Cl); $\nu_{max}$/cm$^{-1}$ (film) 2886, 2628, 1664, 1621, 1574, 1552, 1478, 1447, 1428, 1398, 1267, 1128, 1025, 995, 918, 898, 871, 844, 822, 737, 684, 638, 614, 545 and 466.

#### 4.2.13. 3-[2-(6-Chloropyridin-3-yl)prop-2-en-1-yl]-4-hydroxy-6-methyl-2*H*-pyran-2-one (12c).




Column chromatography eluting with petroleum ether–ethyl acetate 3:7 (v/v) afforded the product (95%) as a colourless solid, which crystallized from ethanol–water as colourless needles, mp 183–185 °C. (Found: C, 60.3; H, 4.35; N, 4.9, Cl, 12.7; $C_{14}H_{12}O_3NCl$ requires C, 60.55; H, 4.35; N, 5.05, Cl, 12.75%); $\delta_H$ (300 MHz, DMSO-$d_6$) 2.15 (3H, s, Me), 3.40 (2H, s, ═C–$CH_2$), 5.0 (1H, s, $CH_2$═), 5.4 (1H, s, $CH_2$═), 6.0 (1H, s, O–C═CH), 7.45 (1H, d, $J$=8.3 Hz, ArH), 7.95 (1H, dd, $J$=8.3, 2.5 Hz, ArH), 8.55 (1H, d, $J$=2.5 Hz, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 19.7 (Me), 28.2 ($CH_2$), 98.2, 100.1, 114.7, 124.1, 135.8, 137.3, 141.2, 147.5, 149.3, 161.1, 164.8 and 166.5 (CO); *m/z* (ES) 281 (33%, $M^+$+H, $^{37}$Cl) and 279 (100, $M^+$+H, $^{35}$Cl); $\nu_{max}$/cm$^{-1}$ (film) 2628, 2302, 1662, 1626, 1558, 1449, 1404, 1265, 1135, 1108, 1053, 1018, 996, 919, 895, 829, 738, 641, 615, and 526.

#### 4.2.14. 3-[2-(3-Chloro-4-fluorophenyl)prop-2-en-1-yl]-4-hydroxy-6-methyl-2*H*-pyran-2-one (12d).

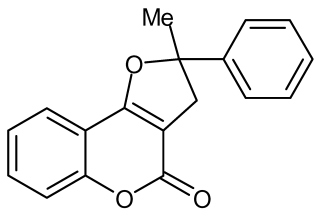



Column chromatography eluting with 1:1 (v/v) petroleum ether–ethyl acetate afforded the product (71%) as a colourless solid, mp 178–180 °C. (Found: C, 60.80; H, 4.50, Cl, 11.75; $C_{15}H_{12}ClFO_3$ requires C, 61.10; H, 4.10; Cl, 12.00%); $\delta_H$ (300 MHz, DMSO-$d_6$) 2.15 (3H, s, Me), 3.35 (2H, s, ═C–$CH_2$), 4.9 (1H, s, $CH_2$═), 5.35 (1H, s, $CH_2$═), 6.0 (1H, s, O–C═CH), 7.35 (1H, t, $J$=9.0 Hz, ArH) ($J$H–H≈$J$H–$^{19}$F), 7.5 (1H, m, ArH), 7.7 (1H, dd, $J$=7.2, 2.0 Hz, ArH); $\delta_C$ (75 MHz, DMSO-$d_6$) 19.6, 28.4, 98.4, 100.2, 113.5, 116.7, 119.7, 126.9, 128.1, 138.9, 142.9, 155.2, 158.5, 160.9, 164.9 and 166.7; *m/z* (ES) 297 (33%, $M^+$+H, $^{37}$Cl) and 295 (100, $M^+$+H, $^{35}$Cl); $\nu_{max}$/cm$^{-1}$ (film) 2616, 1625, 1558, 1504, 1448, 1423, 1401, 1270, 1133, 1086, 1057, 995, 896, 817, 737, 641, 617, 515 and 462.

### 4.3. General procedure C-allylation–cylisation

Allylation was carried out as described above in Section 4.2. The mixture was then cooled to room temperature, excess allene vented, the mixture filtered and the filtrate evaporated under reduced pressure. The brown residue was dissolved in chloroform (10 ml) and trifluoroacetic acid was added dropwise with stirring until the pH of the mixture was approximately 3. The mixture was then stirred at room temperature for 3–4 h, diluted with chloroform (10 ml) and washed with water (2×10 ml). The organic layer was dried ($MgSO_4$), filtered and the filtrate concentrated under reduced pressure. The residue was purified by flash chromatography over silica gel.

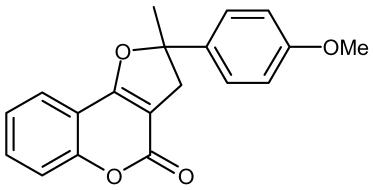
#### 4.3.1. 2-Methyl-2-phenyl-2,3-dihydro-4*H*-furo[3,2-*c*]chromen-4-one (11a).




Column chromatography eluting with 4:1 v/v petroleum ether–EtOAc afforded the product (60%) as a colourless oil. (HRMS: 279.1021 ($M^+$+H); $C_{18}H_{14}O_3$ requires 279.1019 ($M^+$+H); $\delta_H$ (300 MHz, $CDCl_3$) 1.9 (3H, s, Me), 3.35 (1H, d, $J$=15.1 Hz, $CH_2$), 3.45 (1H, d, $J$=15.1 Hz, $CH_2$), 7.3–7.45 (7H, m, ArH), 7.55 (1H, td, $J$=7.1, 1.5 Hz, ArH), 7.8 (1H, dd, $J$=7.8, 1.5 Hz, ArH); $\delta_C$ (75 MHz, $CDCl_3$) 29.9 (Me), 42.0 ($CH_2$), 95.2, 101.9, 113.1, 117.4, 123.2, 124.4, 124.6, 125.1, 128.3, 129.1, 132.8, 145.1, 155.5, 161.1 and 165.7 (CO); *m/z* (ES) 279 (100%, $M^+$+H); $\nu_{max}$/cm$^{-1}$ (film) 3061, 2976, 2923, 2862, 1723, 1646, 1607, 1498,

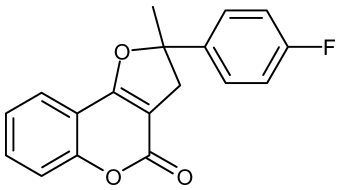
1446, 1409, 1345, 1279, 1213, 1084, 1028, 961, 887, 766, 751, 729 and 699.

#### 4.3.2. 2-(4-Methoxyphenyl)-2-methyl-2,3-dihydro-4*H*-furo[3,2-*c*]chromen-4-one (11b).



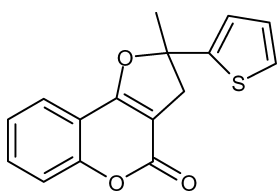

Column chromatography eluting with 4:1 v/v petroleum ether–EtOAc afforded the product (65%) as a colourless oil. (Found: C, 73.7; H, 5.30; $C_{19}H_{16}O_4$ requires C, 74.0; H, 5.20%); $\delta_H$ (300 MHz, $CDCl_3$) 1.9 (3H, s, Me), 3.3 (1H, d, $J$=15.1 Hz, $CH_2$), 3.4 (1H, d, $J$=15.1 Hz, $CH_2$), 3.8 (3H, s, OMe), 6.9 (2H, d, $J$=8.8 Hz, ArH), 7.3 (1H, t, $J$=7.1 Hz, ArH), 7.4 (3H, d, $J$=8.8 Hz, ArH), 7.55 (1H, t, $J$=7.1 Hz, ArH), 7.75 (1H, d, $J$=7.8 Hz, ArH); $\delta_C$ (75 MHz, $CDCl_3$) 29.6 (Me), 41.9 ($CH_2$), 55.7 (OMe), 95.1, 101.9, 113.1, 114.4, 117.4, 123.2, 124.4, 124.4, 126.1, 132.8, 137.0, 155.4, 159.6, 161.1 and 165.7 (CO); *m*/*z* (ES) 309 (100%, $M^+$+H); $\nu_{max}/cm^{-1}$ (film) 3055, 2987, 1719 (CO), 1646, 1516, 1420, 1265, 1032, 896, 737 and 705.

#### 4.3.3. 2-(4-Fluorophenyl)-2-methyl-2,3-dihydro-4*H*-furo[3,2-*c*]chromen-4-one (11c).



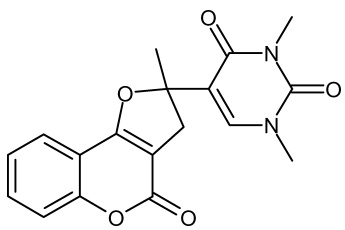

Column chromatography eluting with 4:1 v/v petroleum ether–EtOAc afforded the product (54%) as a colourless oil. (Found: C, 72.7; H, 4.70; $C_{18}H_{13}O_3F$ requires C, 72.9; H, 4.40%); $\delta_H$ (300 MHz, $CDCl_3$) 1.9 (3H, s, Me), 3.35 (1H, d, $J$=15.15 Hz, $CH_2$), 3.4 (1H, d, $J$=15.15 Hz, $CH_2$), 7.1 (2H, t, $J$=8.7 Hz, ArH), 7.3–7.45 (4H, m, ArH), 7.6 (1H, td, $J$=7.3, 1.6 Hz, ArH), 7.7 (1H, dd, $J$=7.8, 1.6 Hz, ArH); $\delta_C$ (75 MHz, $CDCl_3$) 29.9 (Me), 42.1 ($CH_2$), 94.7, 101.8, 113.0, 115.8, 116.1, 117.5, 123.2, 124.4, 126.5, 126.6, 132.9, 140.9, 155.5, 161.0, 164.3 and 165.6 (CO); *m*/*z* (ES) 297 (100%, $M^+$+H); $\nu_{max}/cm^{-1}$ (film) 3066, 2979, 2931, 2866, 1725 (CO), 1647, 1607, 1559, 1512, 1500, 1410, 1279, 1233, 1162, 1101, 1057, 1029, 962, 888, 836, 752, 730, 555 and 540.

#### 4.3.4. 2-Methyl-2-(2-thienyl)-2,3-dihydro-4*H*-furo[3,2-*c*]chromen-4-one (11d).




Column chromatography eluting with 4:1 v/v petroleum ether–EtOAc afforded the product (63%) as a colourless oil. (Found: C, 67.6; H, 4.45; S, 11.0; $C_{16}H_{12}O_3S$ requires C, 67.6; H, 4.25; S, 11.2%); $\delta_H$ (300 MHz, $CDCl_3$) 2.0 (3H, s, Me), 3.35 (1H, d, $J$=15.4 Hz, $CH_2$), 3.6 (1H, d, $J$=15.4 Hz, $CH_2$), 7.0 (1H, dd, $J$=5.0, 3.6 Hz, thienyl H), 7.12 (1H, dd, $J$=3.6, 1.2 Hz, thienyl H), 7.25–7.35 (2H, m, ArH), 7.35 (1H, d, $J$=7.7 Hz, ArH), 7.55 (1H, td, $J$=7.8, 1.6 Hz, ArH), 7.7 (1H, dd, $J$=7.8, 1.6 Hz, ArH); $\delta_C$ (75 MHz, $CDCl_3$) 29.6 (Me), 42.3 ($CH_2$), 92.8, 101.7, 113.0, 117.4, 123.3, 124.4, 124.5, 126.2, 127.4, 132.9, 148.0, 155.4, 160.9 and 165.3 (CO); *m*/*z* (ES) 285 (100%, $M^+$+H); $\nu_{max}/cm^{-1}$ (film) 3429 (br), 2979, 2928, 2868, 1720 (CO), 1646, 1607, 1569, 1498, 1409, 1344, 1280, 1056, 1029, 898, 880, 752, 730 and 705.

#### 4.3.5. 1,3-Dimethyl-5-(2-methyl-4-oxo-2,3-dihydro-4*H*-furo[3,2-*c*]chromen-2-yl)pyrimidine-2,4(1*H*,3*H*)-dione (11e).

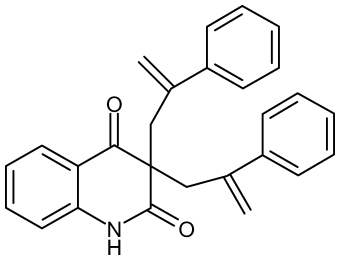



Column chromatography eluting with 4:1 v/v petroleum ether–EtOAc afforded the product (71%) as colourless plates, mp 74–76 °C. (Found: C, 63.5; H, 4.90; N, 8.1; $C_{18}H_{16}N_2O_5$ requires C, 63.5; H, 4.75; N, 8.2%); $\delta_H$ (300 MHz, $CDCl_3$) 1.85 (3H, s, Me), 3.25 (1H, d, $J$=15.9 Hz, $CH_2$), 3.35 (1H, d, $J$=15.9 Hz, $CH_2$), 3.36, 3.45 (2×3H, 2×s, 2×Me), 7.3–7.45 (2H, m, ArH), 7.38 (1H, s, vinyl H), 7.57 (1H, td, $J$=8.7, 1.5 Hz, ArH), 7.72 (1H, dd, $J$=7.7, 1.5 Hz, ArH); $\delta_C$ (75 MHz, $CDCl_3$) 27.4 (Me), 28.3 (Me), 37.8 (Me), 40.1 ($CH_2$), 92.0, 103.1, 112.9, 116.0, 117.5, 122.8, 124.4, 132.8, 138.9, 151.8, 155.4, 160.8 (CO), 161.5 (CO) and 164.6 (CO); *m*/*z* (ES) 341 (100%, $M^+$+H); $\nu_{max}/cm^{-1}$ (film) 3440 (br), 3066, 2983, 2934, 1707 (CO), 1660, 1607, 1500, 1455, 1410, 1366, 1347, 1280, 1254, 1219, 1029, 895, 783, 771, 732 and 700.

### 4.4. General procedure for bis-C-allylation of 4-hydroxy-2-quinolone (2)

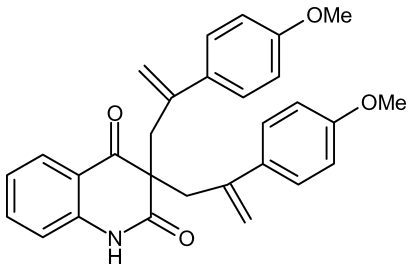
A mixture of aryl iodide (2.1 mmol, 2.1 equiv.), 4-hydroxy-2-quinolone **2** (0.16 g, 1.0 mmol, 1.0 equiv.), tris(dibenzylideneacetone)dipalladium (0.02 g, 2.5 mol%), tris(2-furyl)-phosphine (0.02 g, 10 mol%) and potassium carbonate (0.25 g, 1.8 mol equiv.) in DMF (GPR, 10 ml) was stirred for 15 min in a Schlenk tube. The mixture was then degassed, frozen, evacuated and charged with allene (1 bar). After warming to room temperature it was heated at 60 °C in an oil bath for 16–20 h. The mixture was then cooled to room temperature and excess allene vented. The resulting mixture was diluted with water (10 ml) and extracted with ether (2×20 ml). The combined organic layer was washed with water (2×20 ml), dried ($MgSO_4$), filtered and the filtrate concentrated under reduced pressure. The residue was purified by flash chromatography over silica gel.

#### 4.4.1. 3,3-Bis(2-phenylprop-2-en-1-yl)quinoline-2,4(1*H*,3*H*)-dione-methane(1:1) (9a).



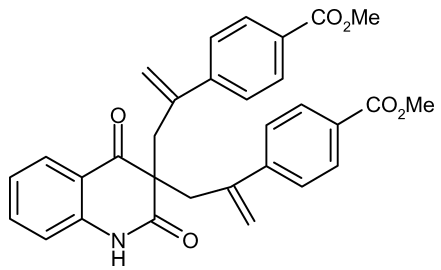
Column chromatography eluting with 4:1 v/v petroleum ether–EtOAc afforded the product (56%) as colourless oil. (HRMS: 394.1808 ($M^+$+H); $C_{27}H_{24}NO_2$ requires 394.1807 ($M^+$+H); $\delta_H$ (500 MHz, $CDCl_3$) 3.30 (2H, d, $J$=14.0 Hz, $CH_2$), 3.38 (2H, d, $J$=14.0 Hz, $CH_2$), 4.88, 5.0 (2×2H, 2×s, 2×C=$CH_2$), 6.66 (1H, d, $J$=7.9 Hz, ArH), 6.85 (1H, t, $J$=7.2 Hz, ArH), 7.05–7.3 (10H, m, ArH), 7.35–7.37 (2H, m, ArH), 9.45 (1H, s, CONH); $\delta_C$ (75 MHz, $CDCl_3$) 46.2 ($CH_2$), 61.2, 116.4, 116.9 ($CH_2$), 120.5, 123.4, 127.2, 127.3, 128.0, 128.2, 135.9, 141.0, 141.1, 144.9, 174.5 (CO) and 197 (CONH); *m/z* (EI) 393 (10%, $M^+$), 275 (35), 262 (40), 115 (80), 103 (30), 91 (100), 77 (60) and 65 (25); $\nu_{max}/cm^{-1}$ (film) 3383, 3190, 3055, 2987, 2932, 2305, 1698 (CO), 1661, 1614, 1599, 1486, 1438, 1385, 1265, 1157, 910, 896, 739 and 704.

#### 4.4.2. 3,3-Bis[(2-(4-methoxyphenyl)prop-2-en-1-yl]-quinoline-2,4(1*H*,3*H*)-dione-methane(1:1) (9b).



Column chromatography eluting with 7:3 v/v petroleum ether–EtOAc afforded the product (41%) as colourless needles, mp 139–141 °C. (Found: C, 76.5; H, 5.90; N, 3.1; $C_{29}H_{27}NO_4$ requires C, 76.8; H, 6.00; N, 3.1%); $\delta_H$ (300 MHz, $CDCl_3$) 3.25 (2H, d, $J$=13.9 Hz, $CH_2$), 3.35 (2H, d, $J$=13.9 Hz, $CH_2$), 3.7 (6H, s, 2×OMe), 4.8, 4.95 (2×2H, 2×s, 2×C=$CH_2$), 6.6 (4H, d, $J$=8.6 Hz, ArH), 6.65 (1H, d, $J$=8.3 Hz, ArH), 6.9 (1H, t, $J$=7.5 Hz, ArH), 7.0 (4H, d, $J$=8.6 Hz, ArH), 7.35 (1H, d, $J$=7.5 Hz, ArH), 7.4 (1H, d, $J$=7.5 Hz, ArH), 8.75 (1H, s, CONH); $\delta_C$ (75 MHz, $CDCl_3$) 46.7 ($CH_2$), 55.6 (OMe), 61.3, 113.4, 115.7, 116.0, 120.5, 123.2, 127.3, 128.5, 133.5, 135.7, 140.8, 144.3, 159.5, 173.9 (CO) and 197 (CONH); *m/z* (ES) 454 (100%, $M^+$+H); $\nu_{max}/cm^{-1}$ (film) 3278 (br, CONH), 3010, 2918, 2836, 1815, 1651 (CO), 1605, 1509, 1378, 1276, 1259, 1180, 1158, 1112, 1029, 949, 906, 837, 805, 764, 748, 696 and 545.

#### 4.4.3. Dimethyl 4,4′-[(2,4-dioxo-1,2,3,4-tetrahydroquinoline-3,3-diyl)diprop-1-ene-3,2-diyl]dibenzoate (9c).

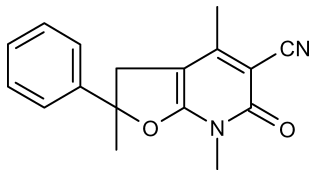


Column chromatography eluting with 7:3 v/v petroleum ether–EtOAc afforded the product (68%) as colourless plates, mp 168–170 °C. (HRMS: 527.2182 ($M^+$+$NH_4$); $C_{31}H_{27}NO_6$ requires 527.2186 ($M^+$+$NH_4$); $\delta_H$ (300 MHz, $CDCl_3$) 3.3 (2H, d, $J$=13.9 Hz, $CH_2$), 3.38 (2H, d, $J$=13.9 Hz, $CH_2$), 3.85 (6H, s, 2×$CO_2$Me), 4.95, 5.1 (2×2H, 2×s, 2×C=$CH_2$), 6.65 (1H, d, $J$=8.0 Hz, ArH), 6.85 (1H, t, $J$=7.5 Hz, ArH), 7.1 (4H, d, $J$=8.3 Hz, ArH), 7.25–7.4 (2H, m, ArH), 7.75 (4H, d, $J$=8.3 Hz, ArH), 9.25 (1H, s, CONH); $\delta_C$ (75 MHz, $CDCl_3$) 45.6 ($CH_2$), 52.5 ($CO_2$*Me*), 61.3, 116.3, 118.8, 120.3, 123.7, 127.1, 129.5, 129.6, 136.4, 140.8, 144.0, 145.7, 167.2, 173.8 (CO) and 197 (CONH); *m/z* (EI) 509 (7%, $M^+$), 333 (45), 320 (50), 174 (25), 115 (100), 102 (50), 91 (45), 77 (42) and 59 (42); $\nu_{max}/cm^{-1}$ (film) 3288 (br, CONH), 3181, 3082, 3005, 2956, 2912, 2851, 1930, 1830, 1717 (CO), 1690, 1608, 1495, 1437, 1396, 1279, 1198, 1109, 1013, 948, 913, 879, 676, 717 and 669.

### 4.5. General procedure for C-allylation–cyclisation of 6-hydroxy-1,4-dimethyl-1,2-dihydropyrid-2-one-3-carbonitrile (4)

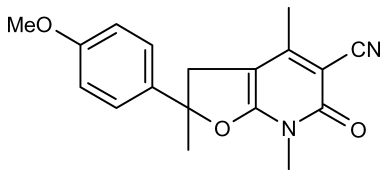
A mixture of aryl iodide (1.0 mmol, 1.0 equiv.), 6-hydroxy-1,4-dimethyl-1,2-dihydropyrid-2-one-3-carbonitrile **3** (1.1 mmol, 1.1 equiv.), tris(dibenzylideneacetone)dipalladium (23 mg, 2.5 mol%), tris(2-furyl)phosphine (23 mg, 10 mol%) and potassium carbonate (0.27 g, 2.0 mol equiv.) in DMF (GPR, 10 ml) was stirred for 15 min in a Schlenk tube. The mixture was then degassed, frozen, evacuated and charged with allene (1 bar). After warming to room temperature, it was heated at 80 °C in an oil bath for 16 h. Upon cooling to room temperature, excess allene was vented, the mixture diluted with ether (20 ml) and washed with dilute aq. trifluoroacetic acid solution. The organic layer was separated and the aqueous layer was further extracted with ether (2×20 ml). The combined organic layer was dried ($MgSO_4$), filtered and the filtrate concentrated under reduced pressure. The brown residue was dissolved in chloroform (10 ml) and trifluoroacetic acid was added dropwise to the stirred solution until pH was approximately 3. Stirring was continued for 3–4 h at room temperature. The reaction mixture was then diluted with chloroform (10 ml) and washed with water (2×10 ml). The organic layer was dried ($MgSO_4$), filtered and the filtrate concentrated under reduced pressure. The residue was purified by flash chromatography over silica gel.

**4.5.1. 2,4,7-Trimethyl-6-oxo-2-phenyl-2,3,6,7-tetrahydrofuro[2,3-*b*]pyridine-5-carbonitrile (16a).**



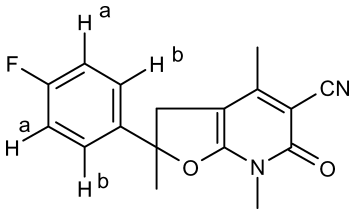

Column chromatography eluting with 9:1 v/v EtOAc–petroleum ether afforded the product (50%) as colourless rods, mp 143–145 °C. (Found: C, 72.6; H, 5.70; N, 10.1; $C_{17}H_{16}N_2O_2$ requires C, 72.8; H, 5.75; N, 10.0%); $\delta_H$ (300 MHz, $CDCl_3$) 1.9, 2.3 (2×3H, 2×s, 2×Me), 3.3 (1H, d, $J$=14.1 Hz, $CH_2$), 3.35 (1H, d, $J$=14.1 Hz, $CH_2$), 3.55 (3H, s, Me), 7.3–7.45 (5H, m, ArH); $\delta_C$ (75 MHz, $CDCl_3$) 19.1 (Me), 29.6 (Me), 30.0 (Me), 42.2 ($CH_2$), 92.3, 95.9, 99.2, 124.3, 128.8, 129.3, 144.0, 155.6, 160.0, 161.2 and 177.1 (CO); *m*/*z* (ES) 303 (100%, $M^+$+Na); $\nu_{max}$/cm$^{-1}$ (solid) 3065, 3035, 2989, 2943, 2879, 2206 (CN), 1654 (CO), 1561, 1292, 1211, 1150, 1089, 1059, 1028, 939, 890, 822, 759, 719, 698, 672, 634 and 523.

**4.5.2. 2-(4-Methoxyphenyl)-2,4,7-trimethyl-6-oxo-2,3,6,7-tetrahydrofuro[2,3-*b*]pyridine-5-carbonitrile (16b).**



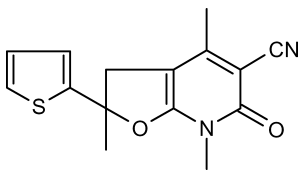

Column chromatography eluting with 4:1 v/v EtOAc–petroleum ether afforded the product (55%) as colourless plates, mp 142–144 °C. (Found: C, 69.5; H, 5.90; N, 9.0; $C_{18}H_{18}N_2O_3$ requires C, 69.6; H, 5.85; N, 9.0%); $\delta_H$ (300 MHz, $CDCl_3$) 1.85, 2.3 (2×3H, 2×s, 2×Me), 3.25 (1H, d, $J$=14.1 Hz, $CH_2$), 3.35 (1H, d, $J$=14.1 Hz, $CH_2$), 3.5, 3.8 (2×3H, 2×s, 2×Me), 6.9 (2H, d, $J$=9.0 Hz, ArH), 7.3 (2H, d, $J$=9.0 Hz, ArH); $\delta_C$ (75 MHz, $CDCl_3$) 19.1 (Me), 29.5 (Me), 29.7 (Me), 42.1 ($CH_2$), 55.8 (OMe), 92.0, 96.0, 99.4, 114.5, 117.2, 125.9, 135.8, 155.5, 159.9, 160.1 and 161.2 (CO); *m*/*z* (ES) 333 (100%, $M^+$+Na); $\nu_{max}$/cm$^{-1}$ (solid) 3104, 2988, 2210 (CN), 1774 (CO), 1624, 1414, 1276, 1261, 1172, 910, 833, 764, 751, 721 and 638.

**4.5.3. 2-(4-Fluorophenyl)-2,4,7-trimethyl-6-oxo-2,3,6,7-tetrahydrofuro[2,3-*b*]pyridine-5-carbonitrile (16c).**



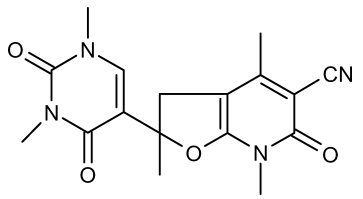

Column chromatography eluting with 4:1 v/v EtOAc–petroleum ether afforded the product (45%) as colourless needles, mp 154–156 °C. (Found: C, 68.1; H, 5.10; N, 9.3; $C_{17}H_{15}N_2O_2F$ requires C, 68.4; H, 5.05; N, 9.4%); $\delta_H$ (300 MHz, $CDCl_3$) 1.9, 2.3 (2×3H, 2×s, 2×Me), 3.3, (1H, d, $J$=14.1 Hz, $CH_2$), 3.35 (1H, d, $J$=14.1 Hz, $CH_2$), 3.5 (3H, s, Me), 7.1 (2H, t, $J$=8.8 Hz, $ArH^a$) ($JH^a-H^b \approx JH^a-^{19}F$), 7.35 (2H, dd, $J$=8.8, 5.1 Hz, $ArH^b$, $H^b$ couples with $H^a$ and F); $\delta_C$ (75 MHz, $CDCl_3$) 19.1 (Me), 29.6 (Me), 30.0 (Me), 42.3 ($CH_2$), 92.4, 95.4, 98.9, 116.1, 116.4, 117.1, 126.3, 126.5, 139.8, 155.7, 159.8, 161.1 and 164.5 (CO); *m*/*z* (ES) 321 (100%, $M^+$+Na); $\nu_{max}$/cm$^{-1}$ (solid) 2943, 2205 (CN), 1661 (CO), 1567, 1511, 1420, 1291, 1230, 1164, 1068, 1028, 891, 834, 760, 717, 646 and 520.

**4.5.4. 2,4,7-Trimethyl-6-oxo-2-thien-2-yl-2,3,6,7-tetrahydrofuro[2,3-*b*]pyridine-5-carbonitrile (16d).**




Column chromatography eluting with 4:1 v/v EtOAc–petroleum ether afforded the product (55%) as colourless needles, mp 129–131 °C. (HRMS: 309.3415 ($M^+$+Na); $C_{15}H_{14}N_2O_2S$ requires 309.3400 ($M^+$+Na); $\delta_H$ (300 MHz, $CDCl_3$) 2.0, 2.3 (2×3H, 2×s, 2×Me), 3.3, (1H, d, $J$=14.3 Hz, $CH_2$), 3.45 (3H, s, Me), 3.5 (1H, d, $J$=14.3 Hz, $CH_2$), 7.0 (1H, dd, $J$=5.0, 4.0 Hz, ArH), 7.05 (1H, m, ArH), 7.35 (1H, d, $J$=4.0 Hz, ArH); $\delta_C$ (75 MHz, $CDCl_3$) 19.1 (Me), 29.5 (Me), 29.6 (Me), 42.5 ($CH_2$), 92.4, 93.5, 99.0, 117.1, 124.9, 126.5, 127.6, 146.7, 155.5, 159.6 and 161.1 (CO); *m*/*z* (ES) 309 (100%, $M^+$+Na); $\nu_{max}$/cm$^{-1}$ (solid) 3100, 2984, 2260 (CN), 1656 (CO), 1555, 1469, 1287, 1207, 1128, 1028, 885, 757, 700 and 657.

**4.5.5. 2-(1,3-Dimethyl-2,4-dioxo-1,2,3-tetrahydropyrimidin-5-yl)-2,4,7-trimethyl-6-oxo-2,3,6,7-tetrahydrofuro[2,3-*b*]pyridine-5-carbonitrile (16e).**




Column chromatography eluting with 4:1 v/v $Et_2O$–MeOH afforded the product (52%) as colourless plates, mp 180 °C (dec.). (Found: C, 59.3; H, 5.35; N, 16.1; $C_{17}H_{18}N_4O_4$ requires C, 59.6; H, 5.30; N, 16.3%); $\delta_H$ (300 MHz, $CDCl_3$) 1.85, 2.25 (2×3H, 2×s, 2×Me), 3.2, (1H, d, $J$=14.7 Hz, $CH_2$), 3.35 (1H, d, $J$=14.7 Hz, $CH_2$), 3.35, 3.45, 3.5 (3×3H, 3×s, 3×Me), 7.35 (1H, s, vinyl H); $\delta_C$ (75 MHz, $CDCl_3$) 19.0 (Me), 27.4 (Me), 28.3 (Me), 29.7 (Me), 37.9 (Me), 40.2 ($CH_2$), 91.7, 93.0, 100.4, 114.5, 117.3, 140.0, 151.7, 155.7, 159.5 (CO), 161.1 (CO) and 161.7 (CO); *m*/*z* (ES) 365 (100%, $M^+$+Na); $\nu_{max}$/cm$^{-1}$ (solid) 2951, 2211 (CN), 1711 (CO), 1655, 1566, 1452, 1368, 1344, 1273, 1211, 1079, 1022, 764, 754 and 519.

## Acknowledgements

We thank Leeds University, the Overseas Research Scheme (ORS) and Tetley and Lupton for support and BASF for a gift of the pronucleophile (**4**).

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